Indian Institute of Technology Madras
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NATIONAL PROGRAMME ON TECHNOLOGY ENHANCED LEARNING

NUCLEAR REACTOR AND SAFETY
AN INTRODUCTORY COURSE
Module 03 Lecture 01
Nuclear Reactors

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So, good afternoon, students. In the last lecture, we had a look at the basic concepts, Physics concepts in the reactors, how the fission reactor -- fission reaction happens, what is the probability of a fission reaction, and what are the fissile elements, what do you mean by the chain reaction and all these aspects, which are related to the fission, production of heat in a nuclear reactor.

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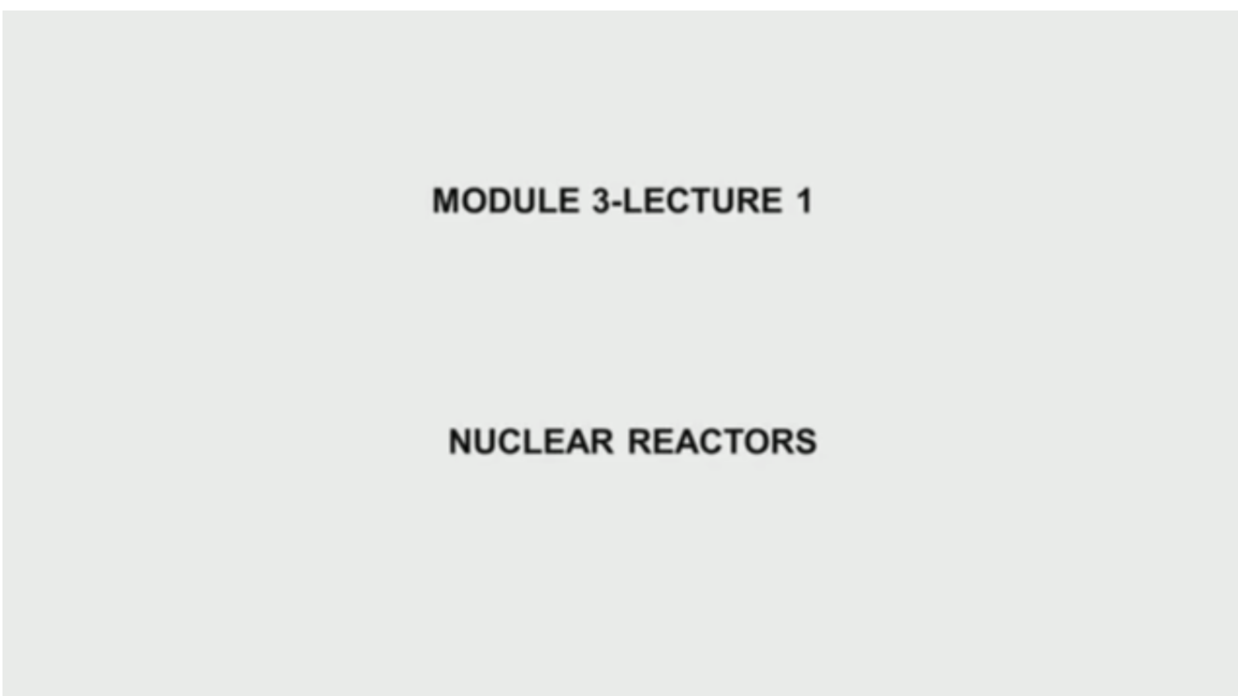

Now we will see what a nuclear reactor is composed of. Now with this background of these basic principles, the major application as we saw is in the nuclear reactors that is for power production, but also in other fields and in this lecture we are only going to touch upon the nuclear reactors about which is the main topic.

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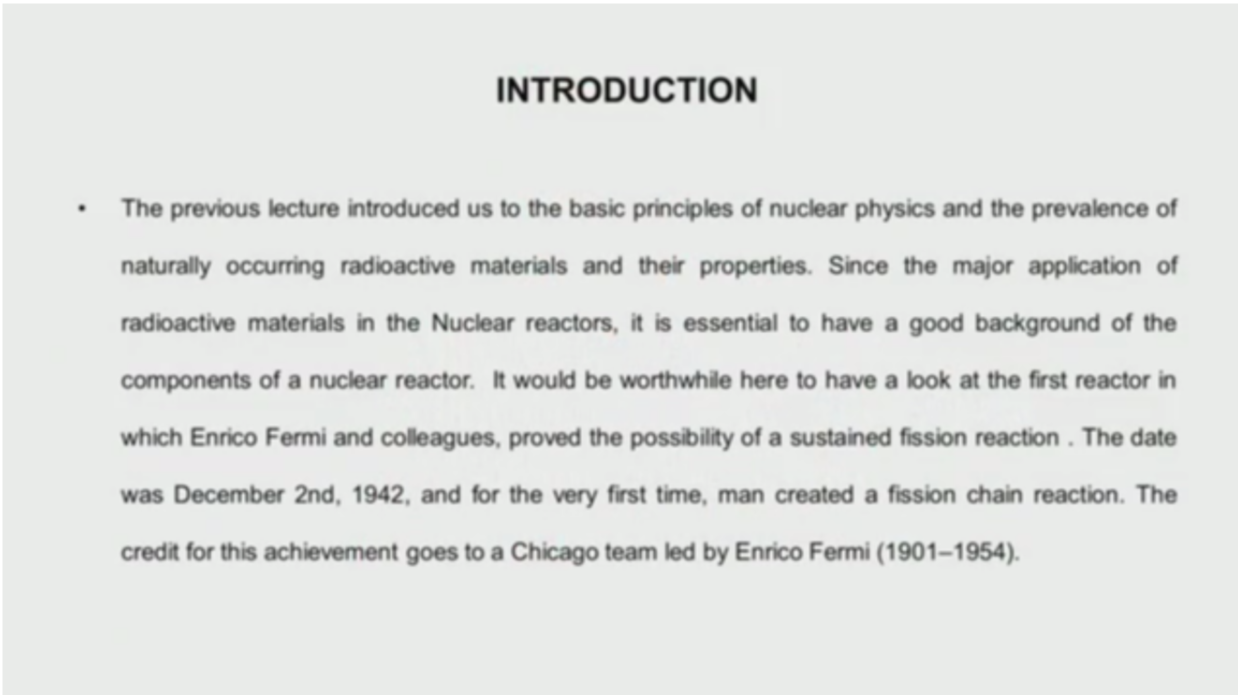

Now you must have heard about the scientist Enrico Fermi. He and his colleagues were able to create a reactor set up where in the fission reaction was sustained. That is they could arrive at a geometry of fissile elements and moderation etc., to come to a reactor and that is called as the Chicago pile and this reactor became critical on December 2nd, 1942. Of course, this is the first time man created a fission chain reaction, but of course it does not -- this -- there is a backup of lot of research done by Enrico Fermi and many other people in this.

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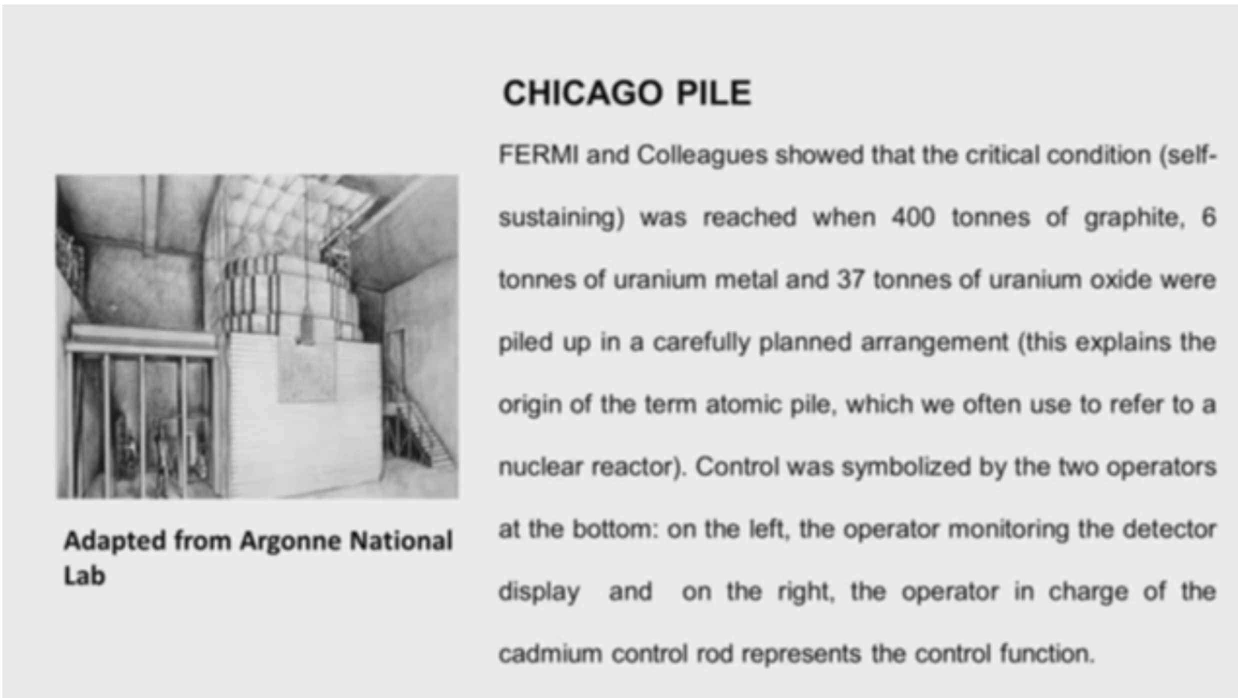

So this is just gives you a picture of the Chicago pile and it contains you see graphite, 400 tons of graphite. Graphite is the moderator here and inside we have 6 tons of Uranium metal and also Uranium oxide, 37 tons of Uranium oxide, and since they are piled up one over the other, this was also called as the pile, so the Chicago pile or the atomic pile as we call it.

Now as I mentioned, moderation is required to have a good fission reaction, good probability of a fission reaction. So the geometry first created. Then you must also have the control and here you have got two operators. See one operator is sitting and he is monitoring the display. Basically, he is looking at the neutron counts whether they are going up or coming down and here you see one operator keeping his hand on a lever arm. This person is actually raising or lowering the control rods.

So what you do? Initially, the control rods are down. So any neutron is there, it gets absorbed. That is now it cannot produce a chain reaction. Slowly, the control rods are raised by this operator and it goes up. At a certain point of time, the absorption is not that much, so the fission reactions start. Now if he raises it more, the fission reactions, number of fission reactions may increase, but that is where he controls. This is a manual control and basically, the rods here were made of Cadmium. So Cadmium control rods were doing the control.

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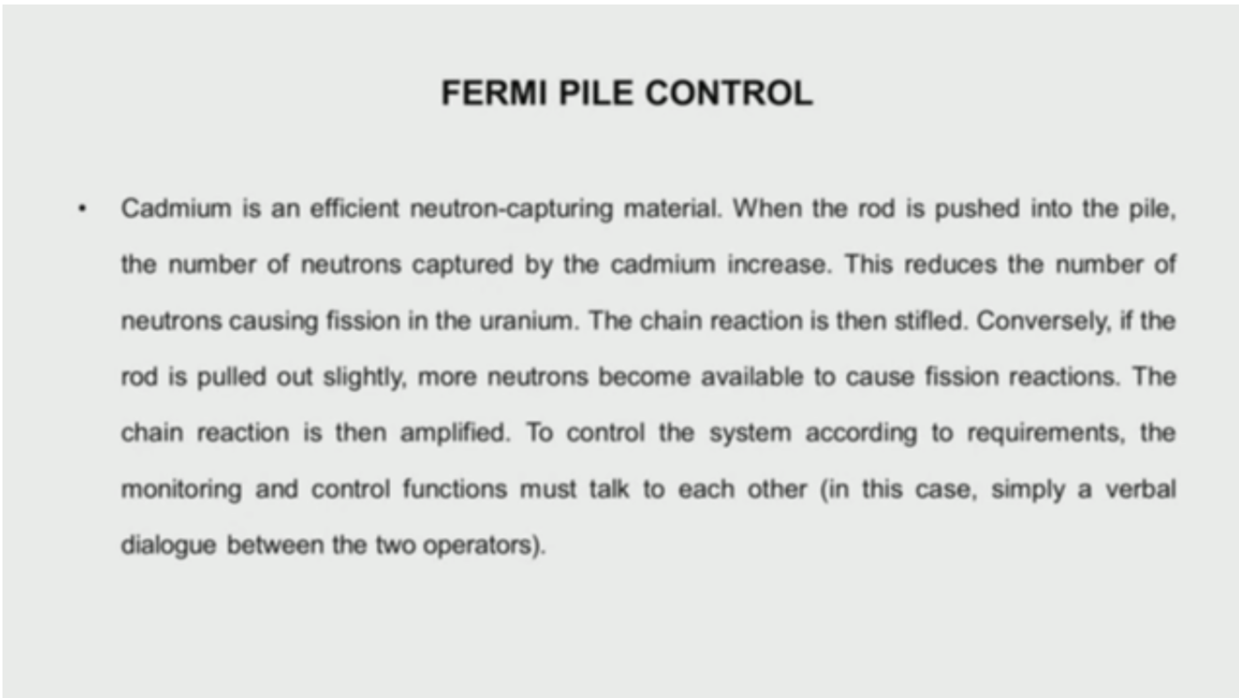

Now Cadmium, Boron, they are all very efficient neutron capturing materials. So what happens? When the rod is pushed inside, it absorbs more neutrons. When it is taken out, it absorbs less neutrons and then tries to maintain the neutron balance.

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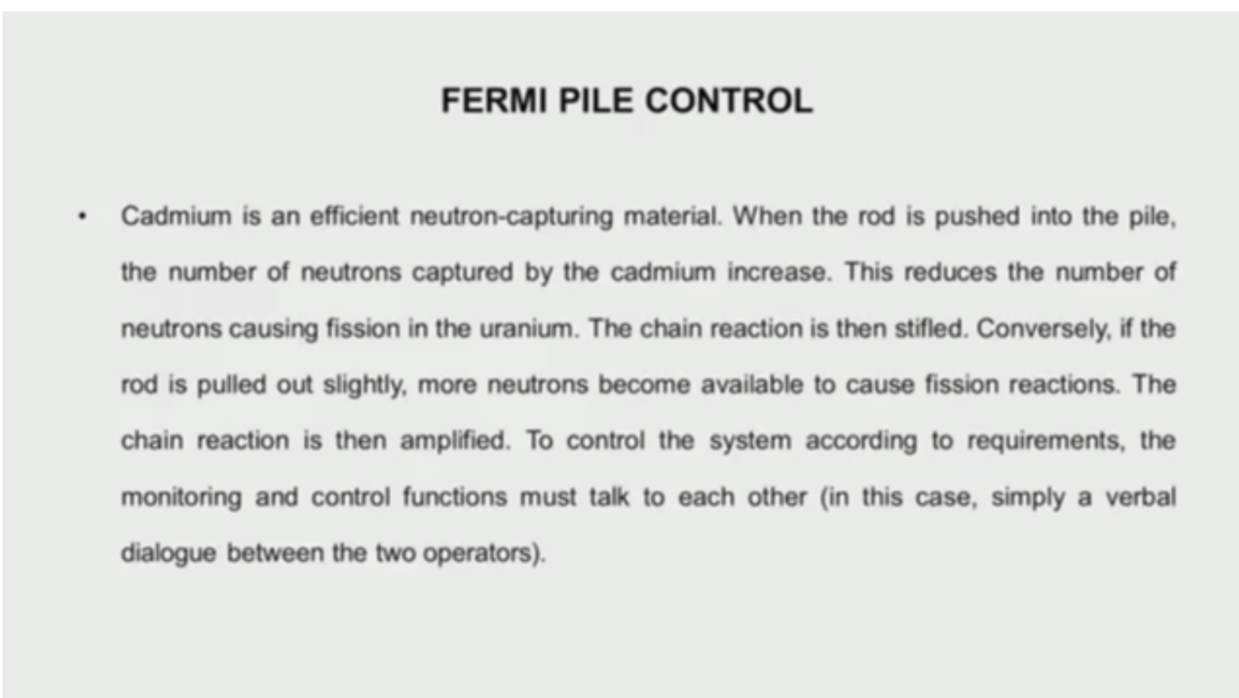

Now this control system and monitoring there is nothing in those days, nothing you know automatic or any, you know, what you call devices or computers available in those days. So the man, the monitoring man and the control man, they will be talking only through voice. So that way they were talking. That's how in this Fermi pile it was controlled.

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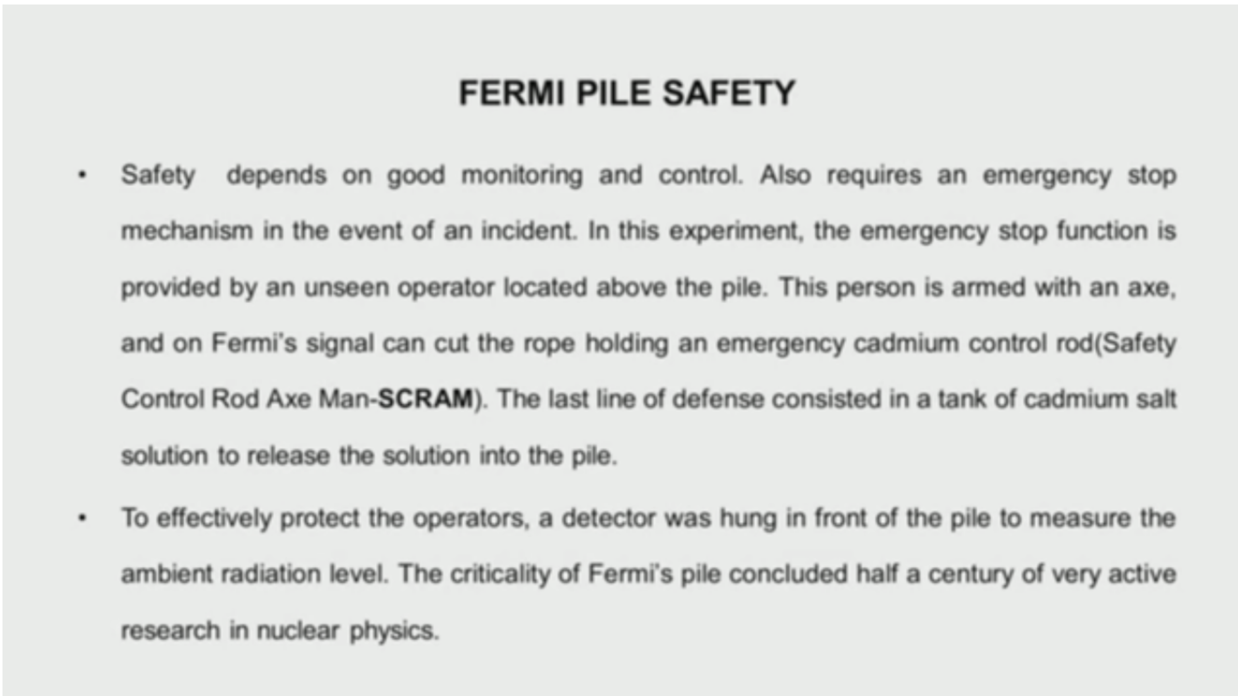

But what I want to emphasize here that awareness of safety, that is if the two fellows who are talking, if there is a bit of a mismatch, the reactor can go supercritical was kept in mind even at that time. So Fermi and his colleagues had thought of an emergency mechanism to take care as the next level. Here this emergency mechanism is actually there are set of control rods at the top which, of course, this is not very visible in this figure.

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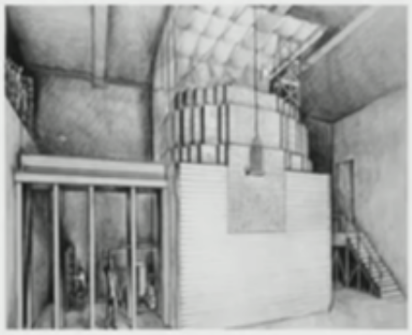
CHICAGO PILE



Adapted from Argonne National Lab

FERMI and Colleagues showed that the critical condition (self-sustaining) was reached when 400 tonnes of graphite, 6 tonnes of uranium metal and 37 tonnes of uranium oxide were piled up in a carefully planned arrangement (this explains the origin of the term atomic pile, which we often use to refer to a nuclear reactor). Control was symbolized by the two operators at the bottom: on the left, the operator monitoring the detector display and on the right, the operator in charge of the cadmium control rod represents the control function.

Somewhere here, it is very, very what you call feeble.

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FERMI PILE SAFETY

- Safety depends on good monitoring and control. Also requires an emergency stop mechanism in the event of an incident. In this experiment, the emergency stop function is provided by an unseen operator located above the pile. This person is armed with an axe, and on Fermi's signal can cut the rope holding an emergency cadmium control rod(Safety Control Rod Axe Man-**SCRAM**). The last line of defense consisted in a tank of cadmium salt solution to release the solution into the pile.
- To effectively protect the operators, a detector was hung in front of the pile to measure the ambient radiation level. The criticality of Fermi's pile concluded half a century of very active research in nuclear physics.

So what they have? A fellow is standing with an axe and for me if suppose he says scram, he will cut the rope and the -- with the axe and the control rods will fall into the core and shutdown the reactor. So one set of rods for control and one set of rods for safety and this SCRAM word itself has emanated from this. It's an acronym for Safety Control Rod Axe Man.

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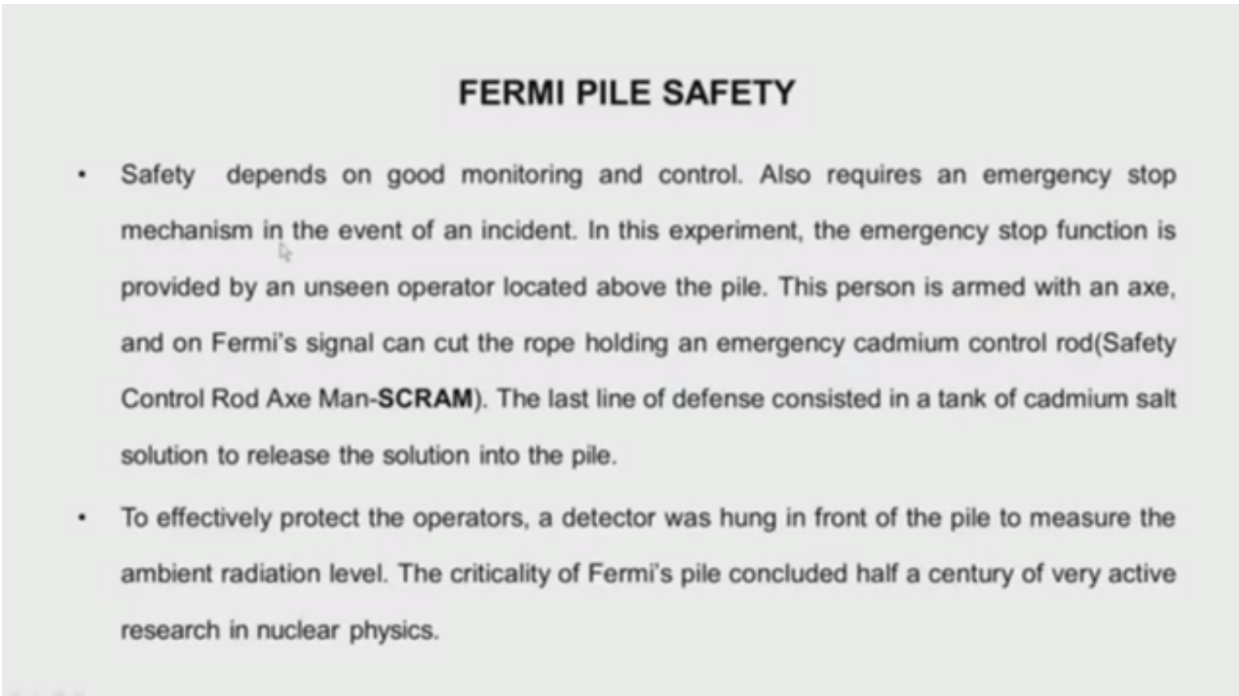

Of course, as the later things went nobody talks of an axe in a nuclear reactor now. So it is still the word SCRAM is used, but it is called as Safety Control Rod Accelerated Movement. This is the explanation or expansion for SCRAM these days. Not only this, remember he had another level of defense. They had a tank containing Cadmium salt solution ready to be poured into the pile and shut down the reaction. So what I want to emphasize here again, safety, backup safety, two lines of safety backup was there.

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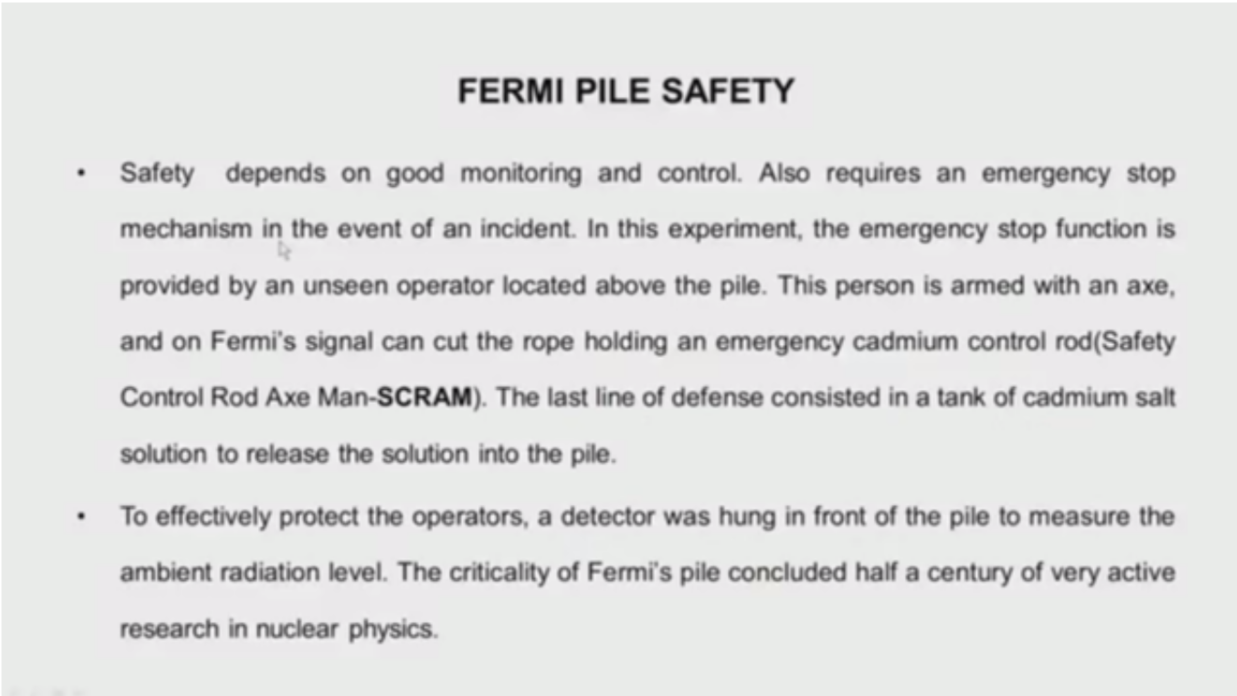

So that safety as a culture in the first reactor pile itself is an example. Now the people are working there around, so they have a detector, which measures the radiation level, and this was used so that the operators how whether they are in which field, radiation field, they should not go to a particular level. Even this was observed right from that time.

Then what is the other component of the -- now let us look at the total components of the any reactor.

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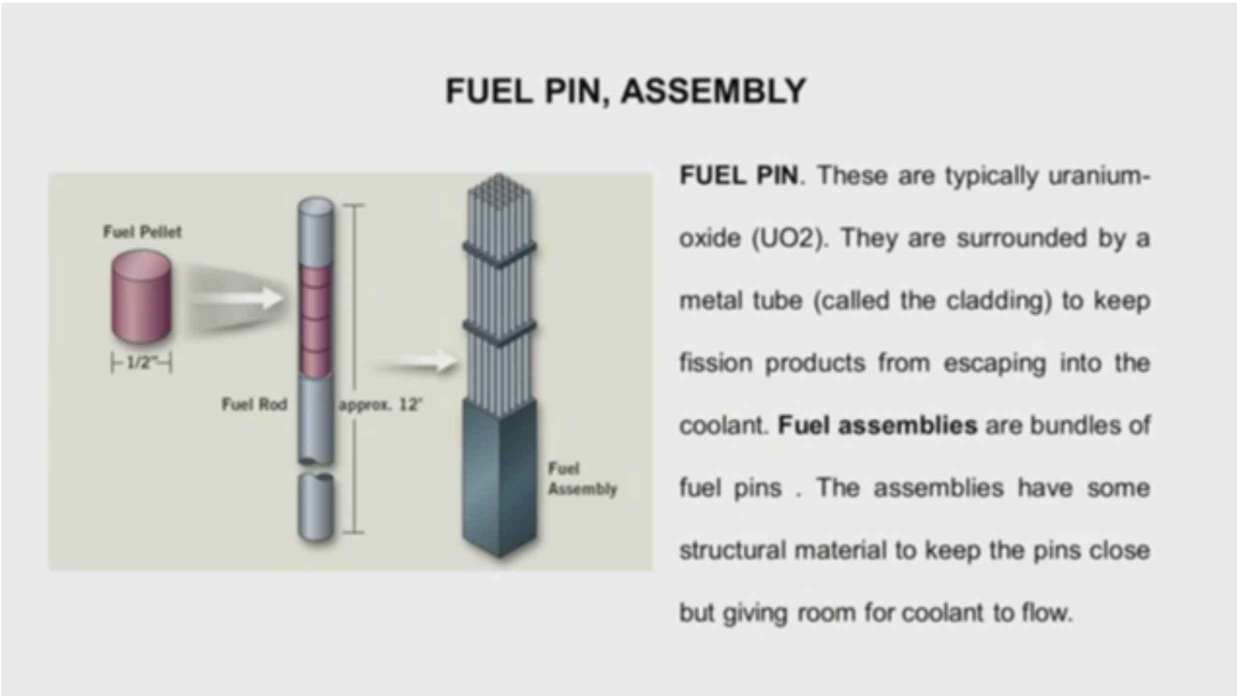

We have the fuel, which is made in the form of pellets. Just to give you an idea it is about half inch diameter and a number of pellets are put inside a camp which is called as the clad, and they are staggered up inside and this we refer to as fuel pin. So this is a fuel pellet. A number of fuel pins becomes a fuel -- fuel pellets become a fuel pin or called as a fuel rod. Then number of such pins are arranged in a rectangular or a hexagonal configuration and they are called as fuel assembly. This rectangular configuration is used in the some type of water reactors. The hexagonal is used in the fast reactors. We will see later. And the fuel is normally Uranium oxide. In the initial days, they did use Uranium metal, but as I mentioned earlier, the melting point of Uranium was low. They couldn't go to high temperatures. Higher the temperature, higher the steam production was possible. Higher temperature, higher efficiency. So they went to Uranium oxide and the clad for all the water reactors was mostly Zirconium because Zirconium is a -- not a very good absorber of neutrons, and the coolant flows inside the fuel assembly and removes the heat produced in the fuel

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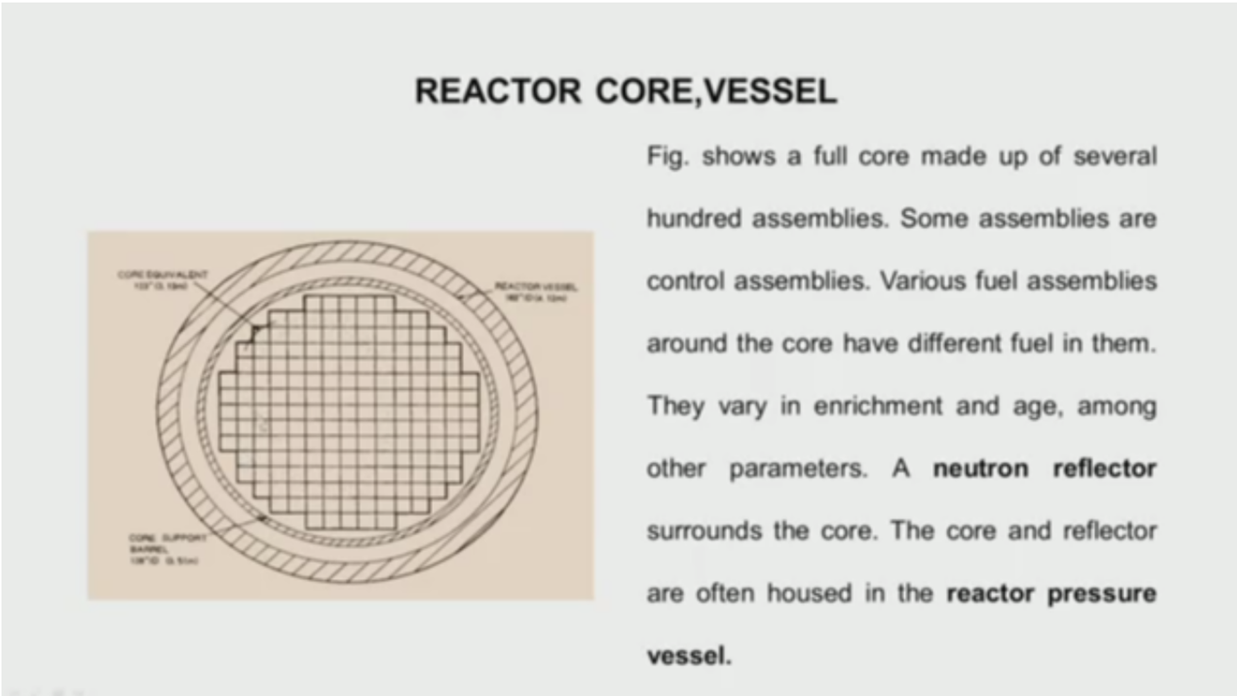

Now many assemblies like this are staggered up and you have the reactor core. Now not shown here are some positions which will have the control rods. There will be a number of control rods so that we have the control on all portions of the reactor.

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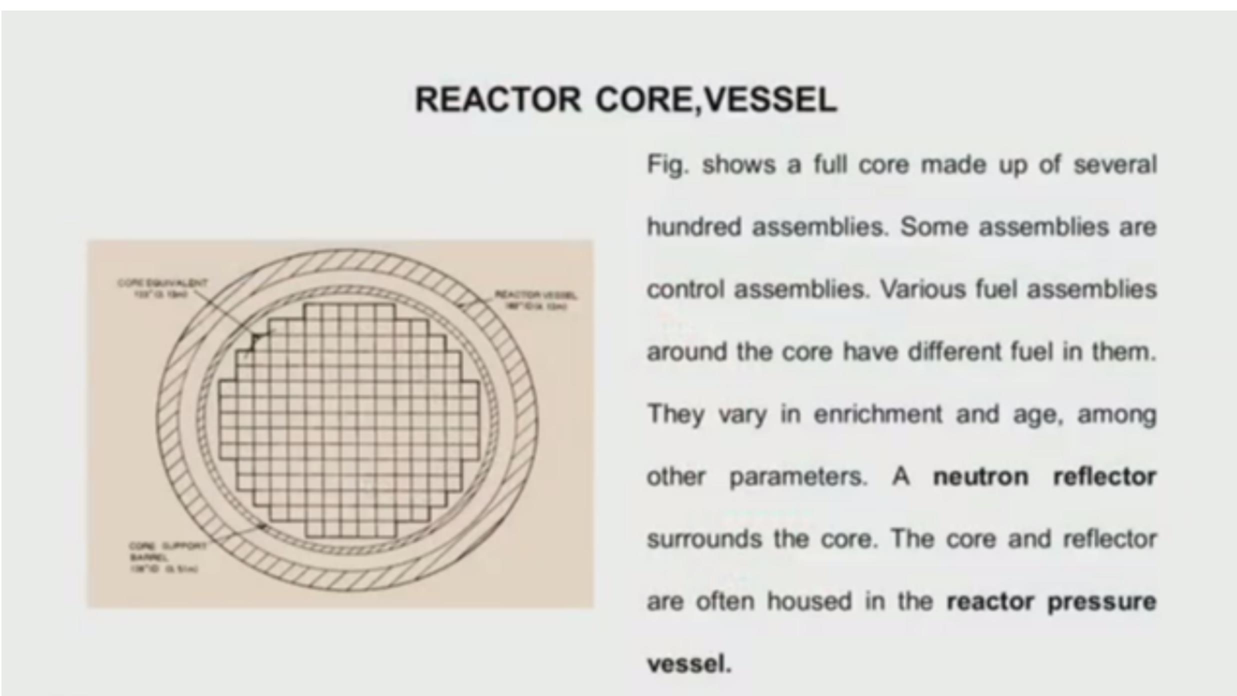

Now within the reactor core, the fuel enrichment may not be same. At the center, it may be lower. Afterwards it is higher because the neutron flux is maximum here. Neutron flux is less on the outside. So to have nearly equal power generation, we have enrichment difference. Now the peripheral assemblies around the core, they are reflecting materials. Normally, we use stainless steel that reflects the neutrons which are coming out or leaking out of the core back to the reactor core. So if the leakage is reduced, all the neutrons, more neutrons are available for the chain reaction.

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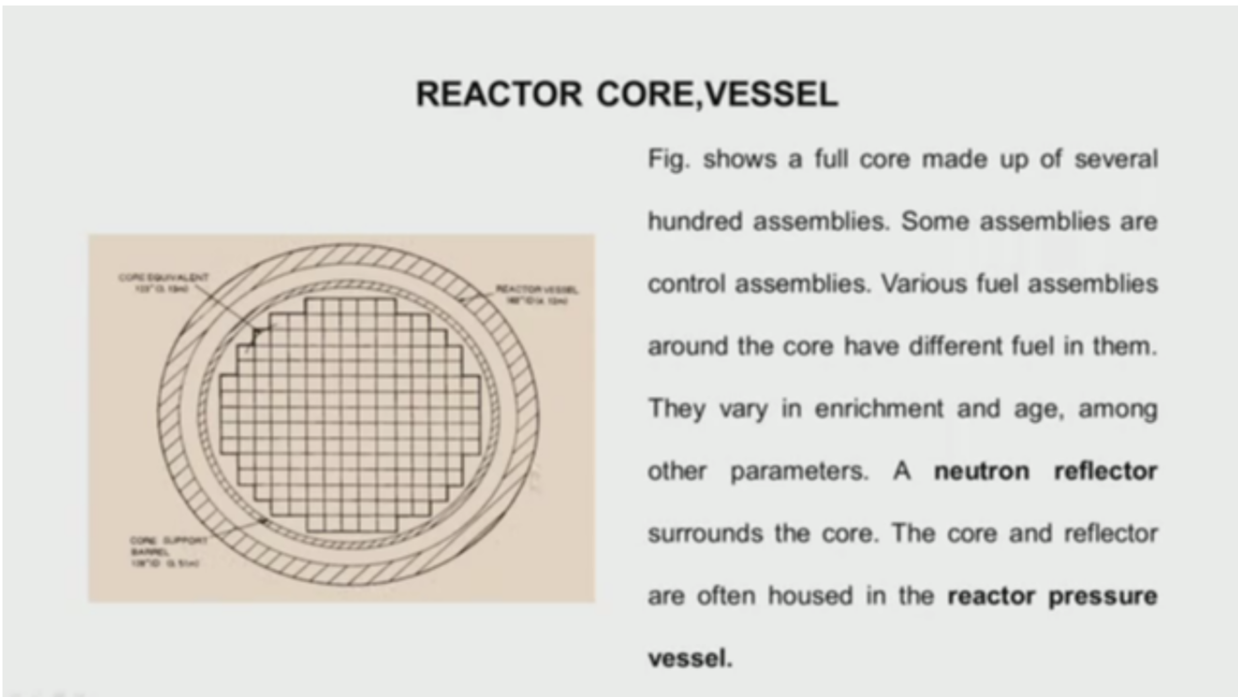

And this whole setup itself is put in a large vessel, steel vessel called as a reactor vessel and of course, it is also a pressure vessel because it has to withstand the pressure of the fluid. So this is a brief idea about what a reactor fuel, a fuel pin, a fuel assembly, or a core or vessel will contain.

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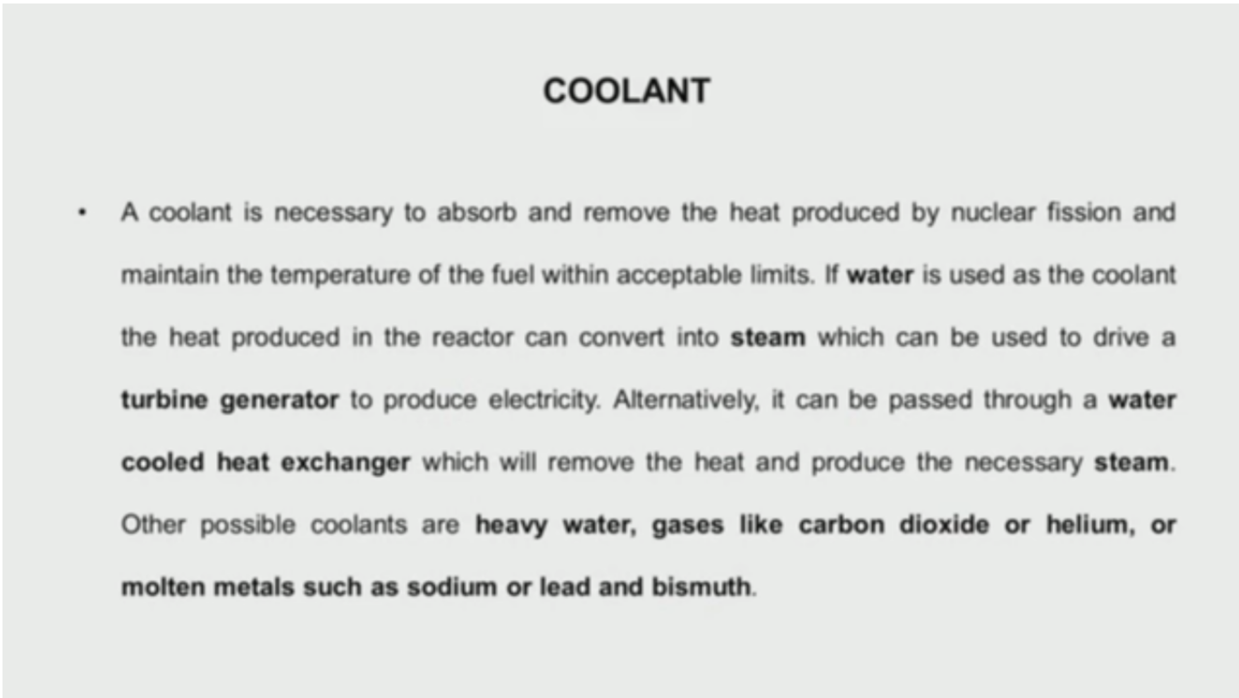

Next is the coolant. Now the coolant is essential to remove the heat which is produced due to the nuclear fission, and not only that, we have to remove the heat. We must also remember that we have to honor the limits on the temperatures, maximum temperatures of the fuel and also the clad material. The coolant maybe it doesn't remove the heat within the temperature, the clad can fail.

For example, if you take Zirconium, the limit is somewhere around 350 to 400 degree centigrade in a water reactor because Zirconium has a very strong reaction with water beyond that temperature. So we do not like to cross that temperature. Similarly, on the fuel side, the melting point should not cross -- should be crossed. So this coolant does this job. In other words, coolant maintains the temperature of the fuel and structure the clad within limits and this water, if used as a coolant, it gets converted into steam and this steam is taken to run a turbine, which rotates the generator and produce electricity. This is one way directly producing steam from the reactor and going to the turbine. Of course, this concept is called used in the boiling water reactors as we shall see later.

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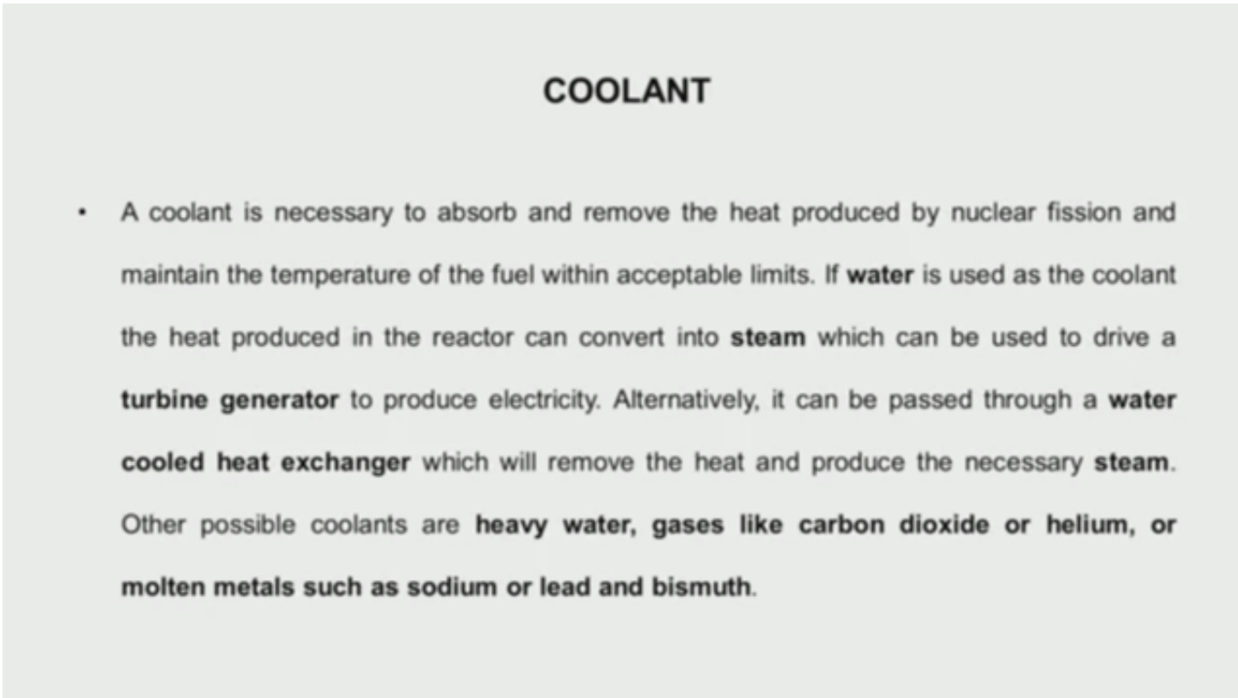

Alternately, this water, which is picking up the heat from the reactor core is sent to a heat exchanger where it exchanges heat with another water, which is converted into steam and that runs a turbine generator. That is you have two cycles. The first primary heat transport and then the secondary water also. This sort of concept is what is called as the pressurized water reactor and that pressurized water reactor is the maximum number in the whole world.

If you look at coolants, any other coolant we can think of, heavy water is a coolant, but heavy water directly we don't convert it into steam and use it because heavy water is a very costly material. So heavy water we use in the heavy water reactors. We shall see description later. Then we could use gas as a coolant like Carbon dioxide or Helium could be used as a coolant. In fast reactors, we use Sodium or we are now even thinking of using Lead or Bismuth, Lead Bismuth alloy. So these are all the coolants. So a reactor contains the fuel, the core, the coolant.

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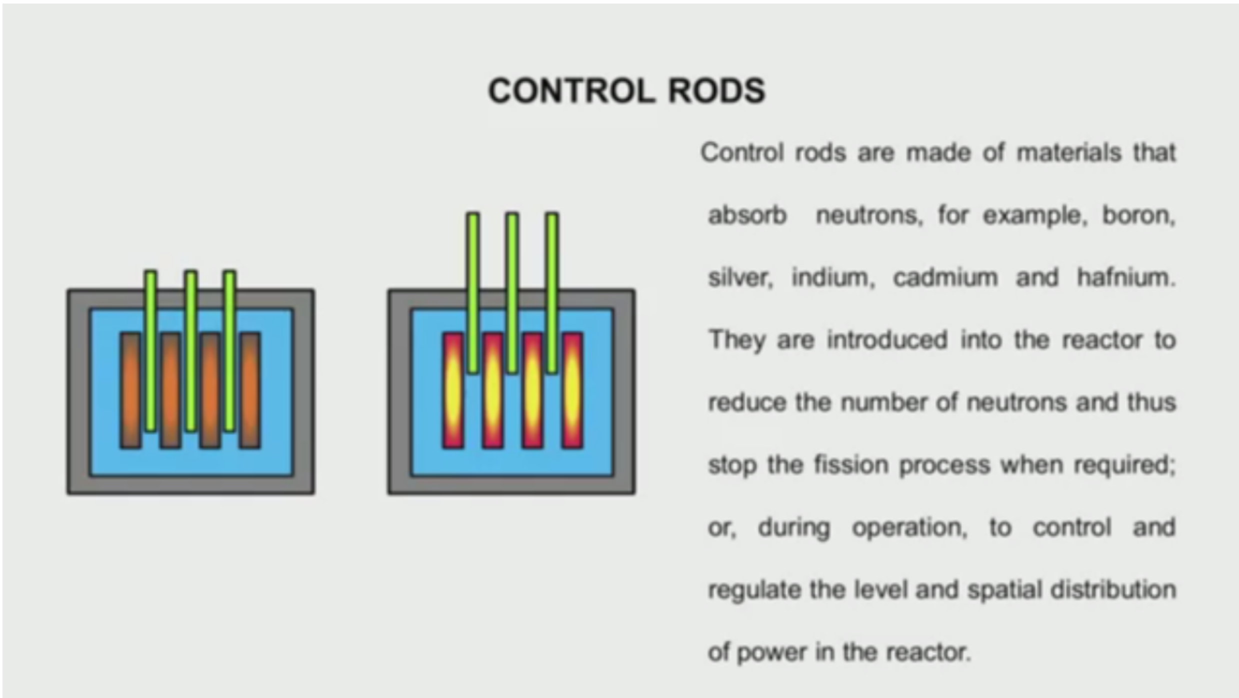

As I mentioned control rods most important from safety point of view and control, and we have mostly used Cadmium and Boron, Of course, there are other materials like Indium, Silver also. Silver is a very costly material and we have a number of rods, not one, so that we have a uniform sort of power production everywhere and uniform temperature as uniform as possible. Now when these rods are down, that means the reactor is shutdown and to raise the thing, the rods are raised, and when it's on power, you see the color becoming red. This shows that the reactor is producing heat.

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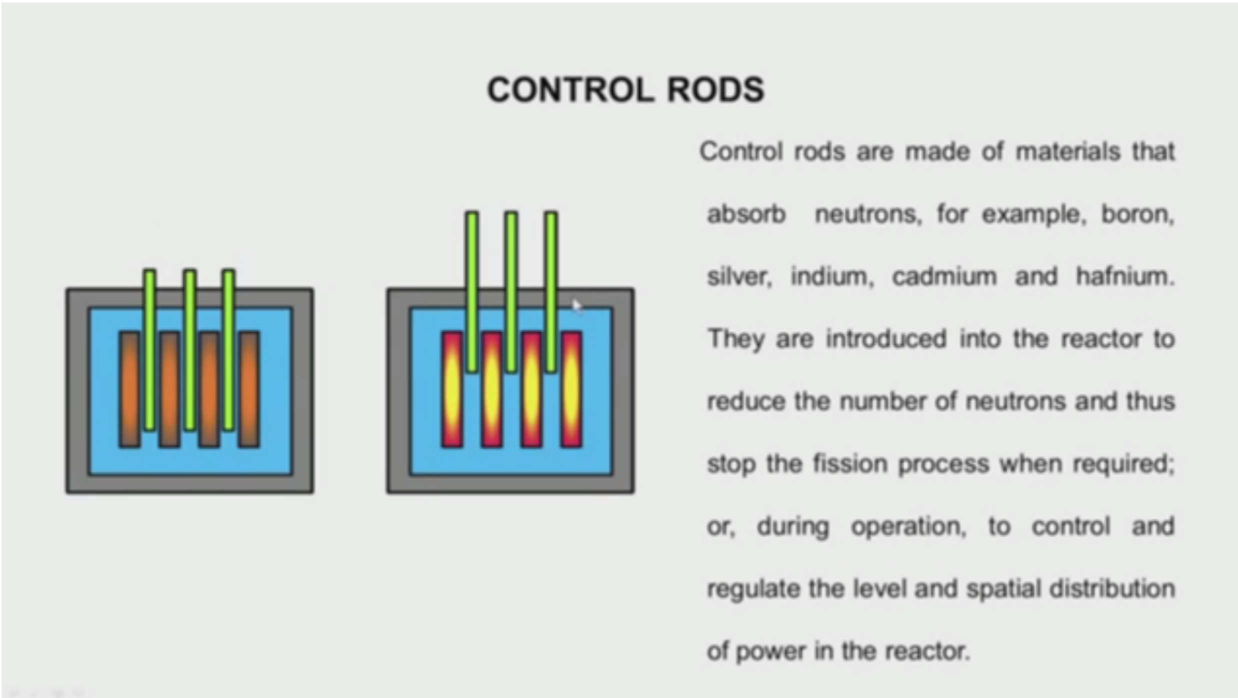

Now if I want to control the power, I will reduce the height, bring it inside and maintain it at level. The neutron population will come down and then stabilize at another level. Then that way my power would have been brought down. If I want to increase the power, I slightly rise one by one. Not all rods are raised. Only one by one at a time.

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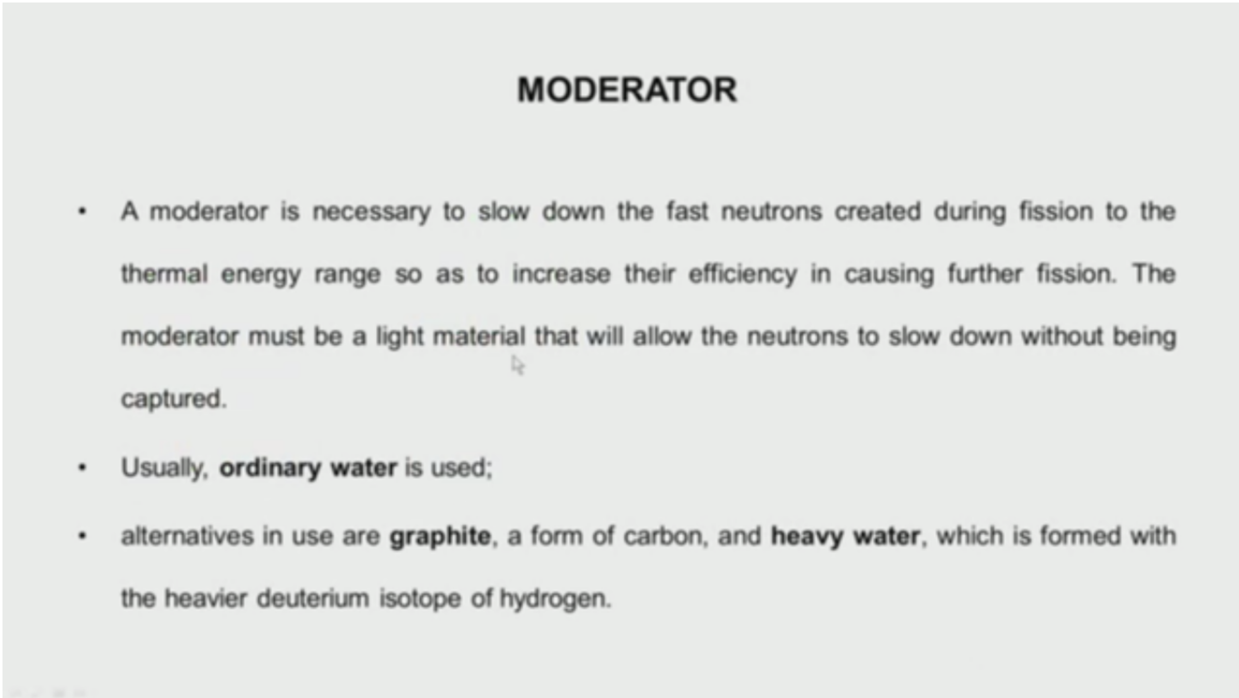

Moderator we saw is an important and the moderator should be efficient so that we can have large number of slow neutrons and large number of slow neutrons means more number of fissions. Light water is one of the moderators. Graphite, I also mentioned about heavy water, the advantage being it has less of absorption than light water, but of course there is a price you have to pay. It is -- it is costly.

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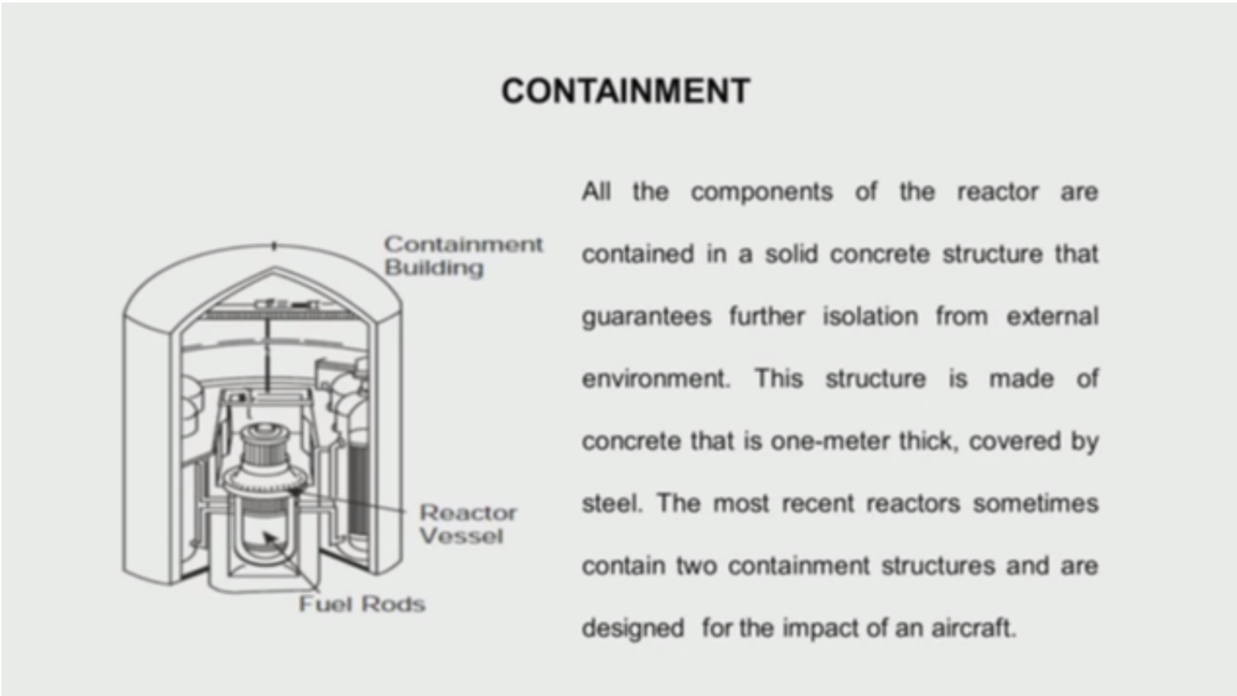

Now we have seen the reactor vessel is there. There is always again a factor which is motivated by the safety aspect. Should something happen and the reactor vessel fails, the component, the radioactive fuel can come out in case of an accident. So all reactors have -- are actually contained in a solid building concrete structure, that again gives isolation from the environment so that the environment is does not get the radiation in case of an accident. Normally, it is made of concrete. Concrete is also a good neutron absorber and is a very good shield.

In some of the reactors, we have basically Indian pressurized heavy water reactors, we have one containment building, there is a gap in another containment, two containments also and these containments, believe it, they are also designed so that any external attack by an aircraft should not -- that containment building should not fail because it is very much important. We think about it nowadays only because we -- terrorists can bring an aircraft and then crash it on your reactor to spoil your program. So here also that has been considered.

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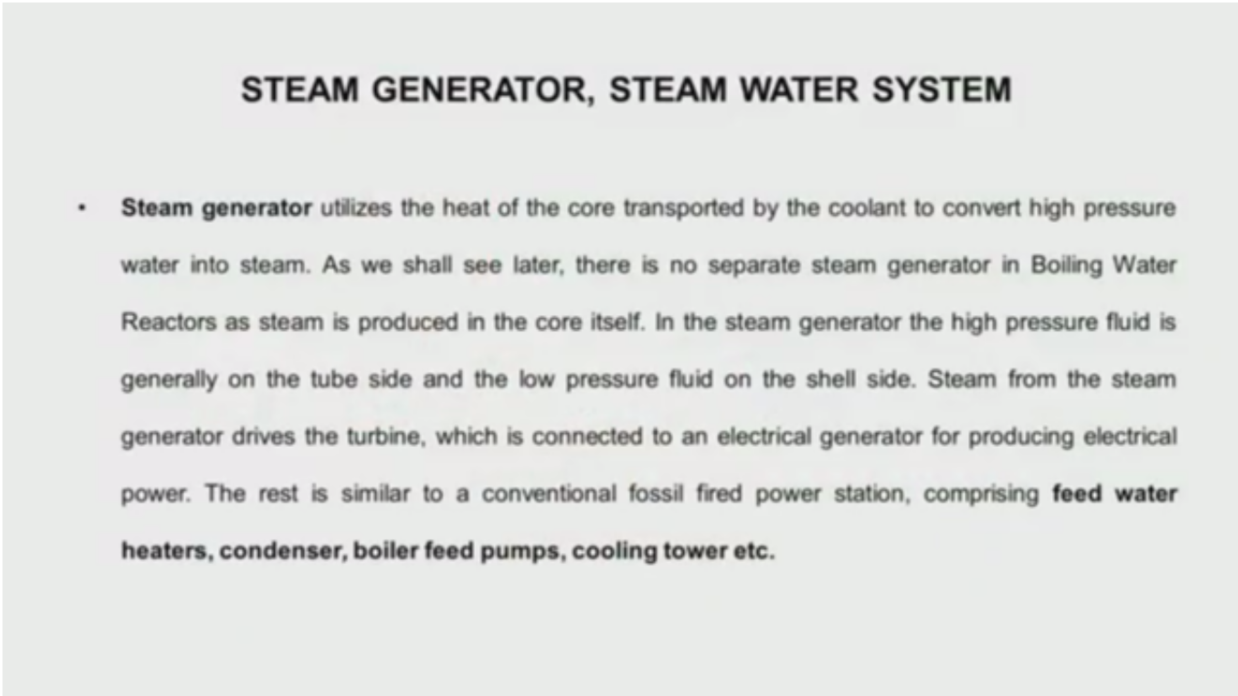

Now the steam -- the steam is produced in a heat exchanger. Normally, heat exchangers which produce steam are called as a steam generator. It generates steam, so it is a steam generator, and it is a high-pressure steam. So this high-pressure steam is sent to a turbine and generator and rest of the system, a feedwater system. Then it has a condenser boiler just like in any other fossil fire plant. We will just have a look how -- which are the components.

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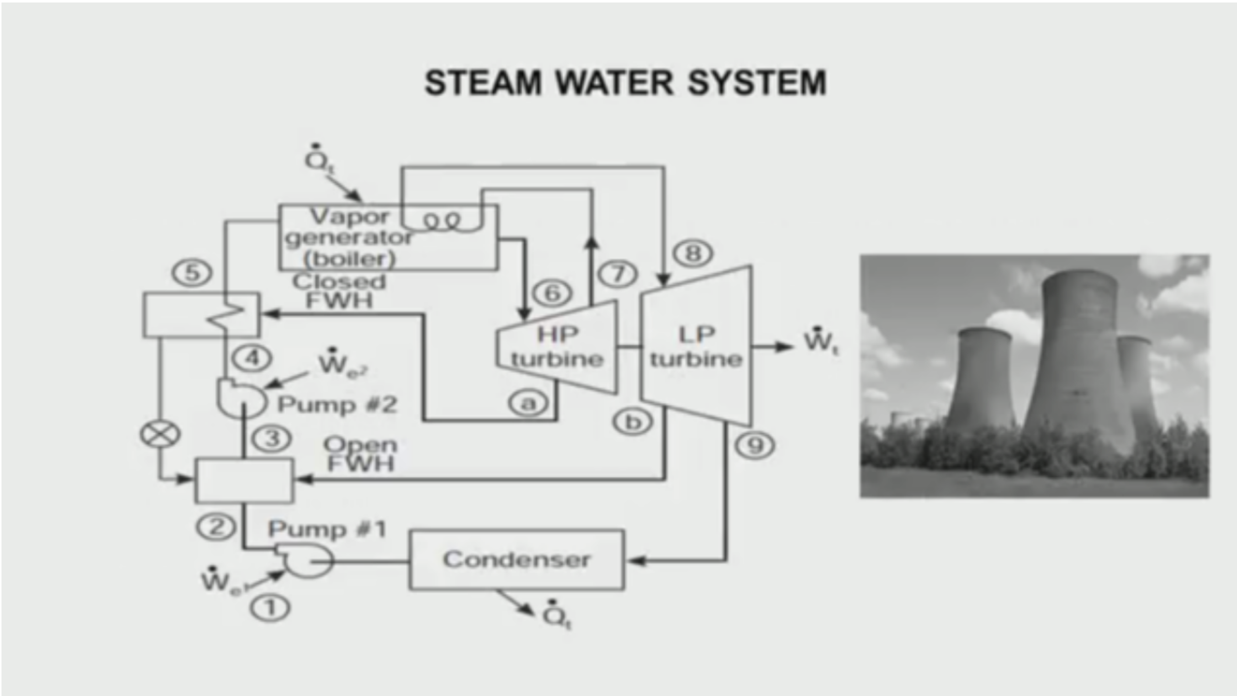

See here this is a steam generator. The steam which is produced goes here. It is a high pressure turbine. It does work in the turbine, but as it does work in the turbine, the quality of the steam comes down and at some stage, it becomes wet. Now you see the turbines use very fine thin blades. So there is a limit on the amount of wetness that they can withstand because any water particles will cause erosion of the blades. So, normally, it is about 10 to 12% wetness. More than that it cannot be there.

So what we do? When it is around about 8 to -- 8 to 10%, we take out the steam and we again heat it up, and remove the moisture, and heat it up, and put it in a low pressure turbine and in the low pressure turbine after doing the work, it is very wet. It has got practically no heat. It is taken out. It is condensed.

What do you do for condensing? The steam is flowing and we have tubes carrying water, cooled -- cold water and this water could be drawn either from a river or something like a cooling tower. This cooling tower is used where there are no rivers. If a river is there, we take a river water. If see is there, we take a sea water and cool it. The condensed water is pumped to heaters, which are called feed water heaters. There could be two stages, there could be three stages and again, the feed water enters to the boiler or the steam generator. So this is the conventional steam water system and it is no different in a nuclear power plant. So it is same as in a fossil fired plant.

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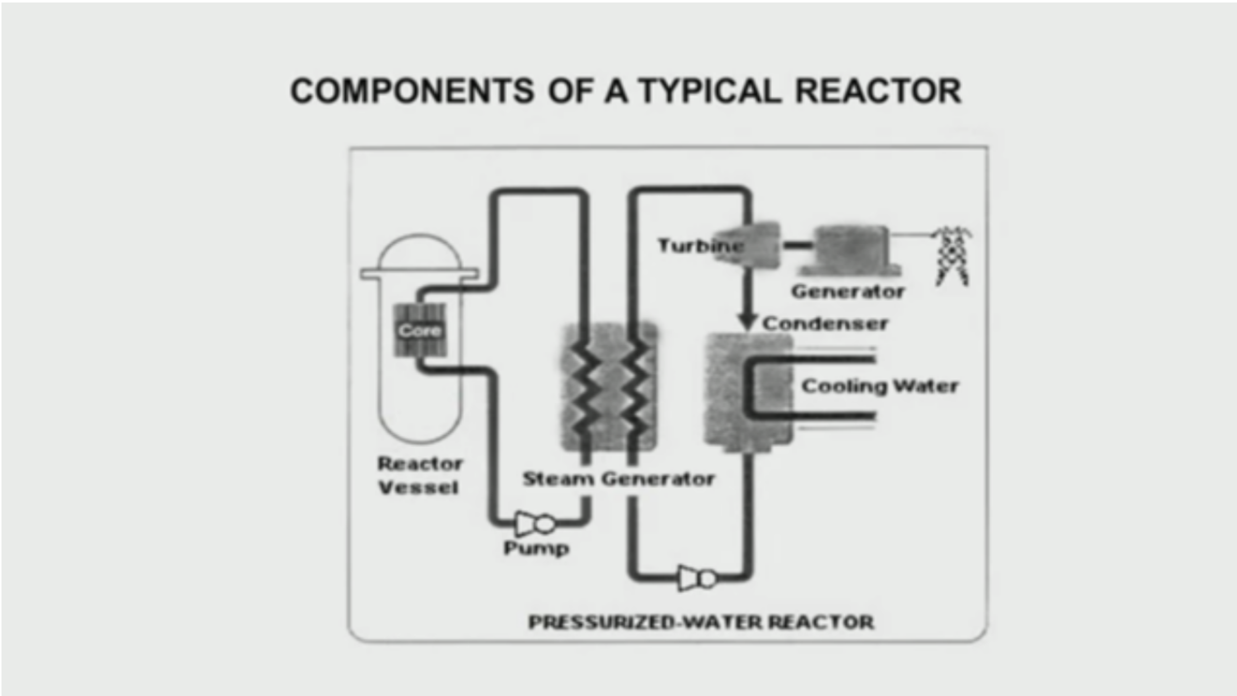

This is to show you what components are there in a typical reactor. Of course, I have taken a pressurized water reactor. The core is there. This is a reactor vessel. The coolant goes, picks up the heat, comes out, exchanges heat in the steam generator, comes back, again, is pumped back to the core. So this is cycle continues. On the secondary side, you have water entering the steam generator, becomes steam, runs the turbine, turbine runs the generator, condenser and then coming back, pumped back to the -- so these are very typical and of course, this is showing the electricity, showing the electrical tower.

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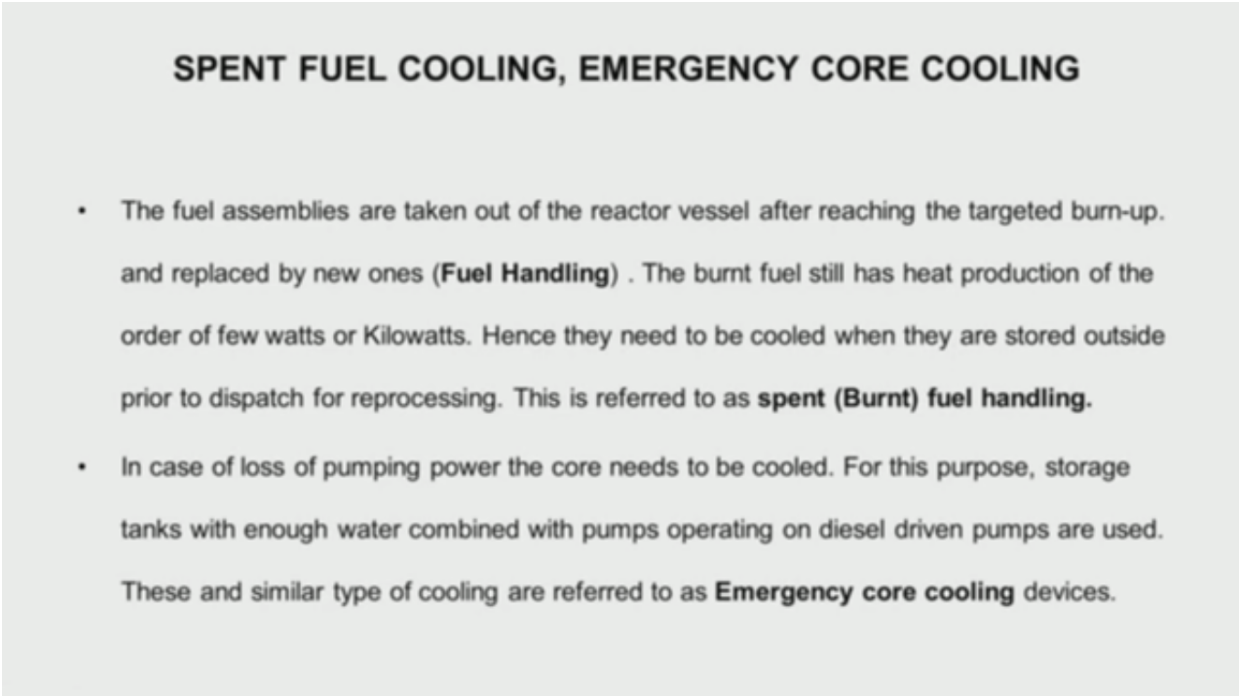

Okay. Now these systems we have seen and as I mentioned, even after you shut down the reactor, you must have cooling provided to the reactor so that the fuel elements are -- temperatures are maintained below the acceptable limits. Now you take out the fuel. After it has been burnt up a certain level and then you replace it by a fresh fuel.

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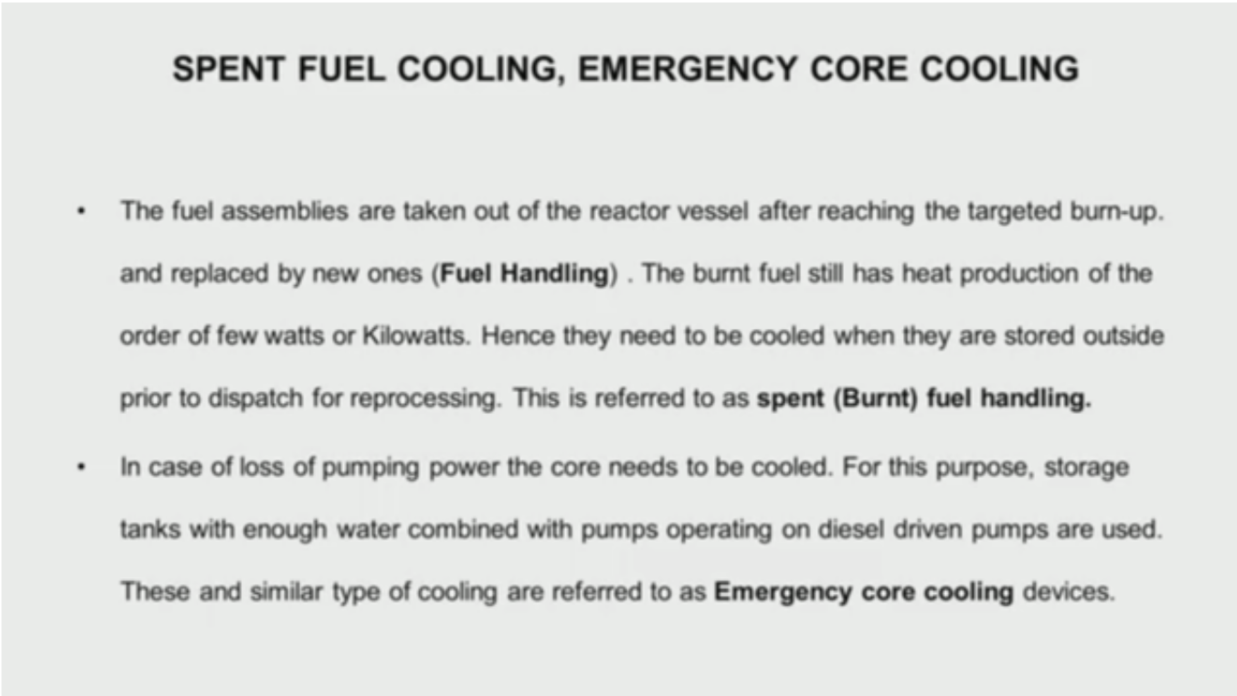

Now this burned up fuel or the spent fuel needs to be again cooled. You can't just keep it in the air. You have to -- it has to be cooled because it depends on the power level at which you are taking out. Roughly on an average, if the heat, decay heat is less than about 400 watts to 600 watts, maybe air cooling could be sufficient, but normally it is high of the order of some kilowatts, so it needs to be kept in cooling base or cooling ponds for quite some time.

So this spent fuel cooling is very, very important. This is cooled because it cannot be handled immediately for reprocessing. The temperatures are also high. Temperatures we brought down. The activity has to be brought down. Then only it can be used for sent for reprocessing. So the spent fuel handling is another.

Fuel handling, again, we require machines for that, change -- taking out the fuel, putting the fuel. So that is a very complicated mechanical system and that is really for a mechanical engineer that is a real what you call real design. He can get the satisfaction and the spent fuel handling is the other portion.

Now coming to the reactor core, let us say we had a power failure and then the pumps will not be running. So in that case, we have to provide some emergency power to run the pumps or in case you are not able to run those pumps, some other means by which we can cool the core to remove the decay heat. Believe it or not, two aspects need to be remembered. Reactors shut down and decay heat removal, these two aspects are to be kept in mind at every level, for every event this must be possible.

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REACTOR TYPES

Reactor Type	Number	GWe	Fuel	Coolant	Moderator
PWR	271	270.4	Enriched UO_2	Water	Water
BWR	84	81.2	Enriched UO_2	Water	Water
CANDU	48	27.1	Natural UO_2	Heavy Water	Heavy Water
GCR	17	9.6	Enriched UO_2	CO_2	Graphite
RBMK	11	10.4	Enriched UO_2	Water	Graphite
SFR	6	0.6	PuO_2 UO_2	Sodium	NIL

Coming to the reactor types, I shall describe each reactor how it looks like later. The pressurized water reactor is the maximum number about 271. The boiling water reactor is about 84. The Three Mile Island was a pressurized water reactor. Fukushima was a boiling water reactor, and this is a CANDU or a heavy water reactor. This is mostly in India, Canada, Argentina, and Pakistan. Then we have the gas cooled reactors, few of them, and this is again RBMK, this is a boiling word reactor, but there's a difference between this and this, which we shall see later and sodium-cooled fast reactor. There are about six such reactors and we have one such reactor in India.

If you see the coolant or if you see the fuel, they use enriched Uranium oxide in both the light water reactors whereas natural Uranium oxide is used in the heavy water reactors. Again, these use enriched fuel. Of course, surely, the fast reactor use enriched fuel along with Plutonium. The coolant here is Sodium. We shall see later how, why, whereas in gas cooled it is Carbon dioxide. Moderator varies from light water here to the heavy water here, graphite, and of course in a fast reactor, there is no moderator.

Gas cooled reactor, this reactor was concept was thought of in United Kingdom and France, and this Magnox reactor is cooled by Carbon dioxide is a gas. The fuel used is enriched Uranium and the clad is Magnesium Oxide. That's why it was called as Magnox, and the moderator is graphite and you have control rods. The gas comes here, goes to a steam generator where steam is produced and the -- it is producing electricity. Here they were able to reach temperatures as high as 600 degree centigrade, but then there were lot of failures of this Magnox clad due to reaction with water.

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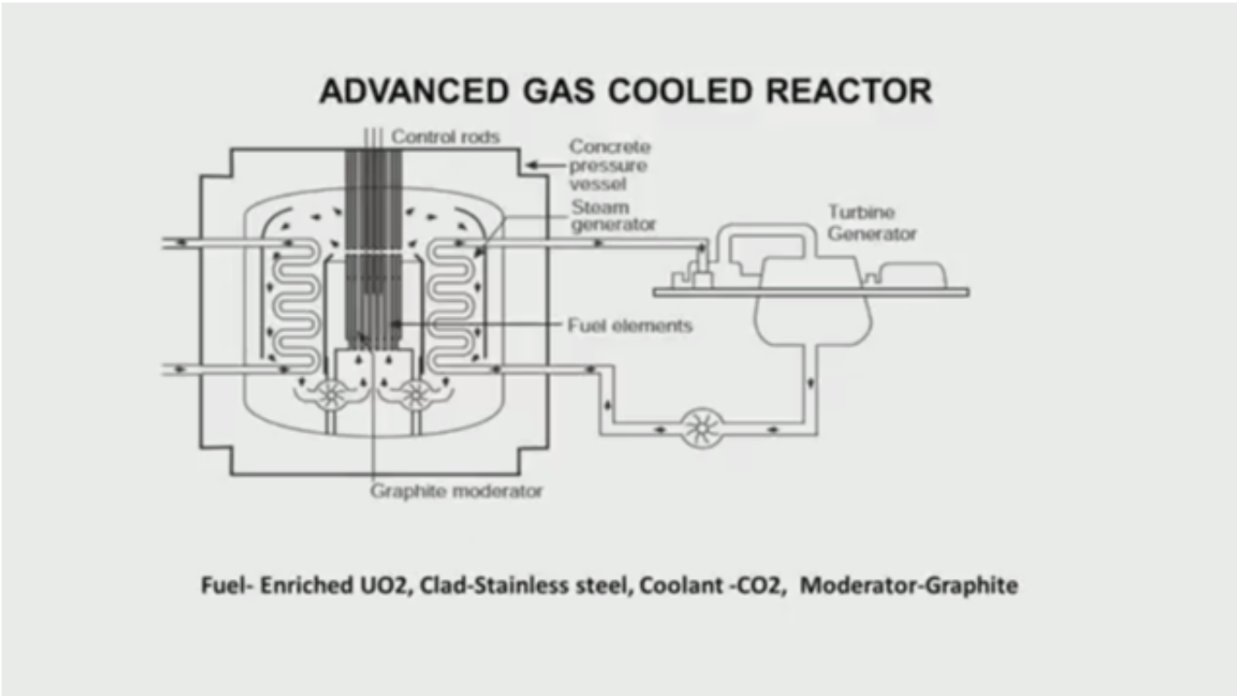

So with the experience gained in these reactors, they moved to the next one where they started using stainless steel as the clad and while the moderator remained graphite and the coolant was still Carbon dioxide, but one more difference they did, earlier they had used a vessel, steel pressure vessel and now they have gone for a concrete pressure vessel. That was the difference. That is more as a safety aspect. So otherwise things remain same and these reactors operated for quite some time. Some of them are still operational in UK.

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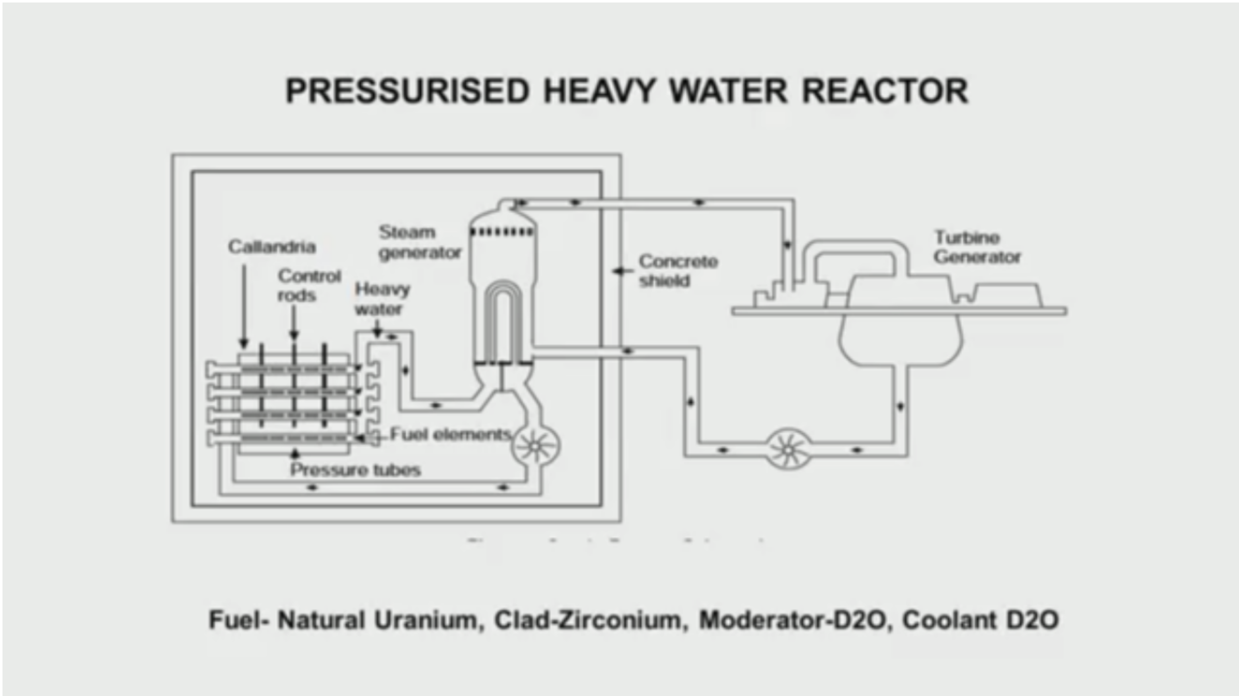

Then this pressurized heavy water reactor. This is our mainstay of India's power program. We have nearly 22 such reactors, most of them about producing about 200 to 220 megawatt electrical each, and some of them are now producing 500 megawatt electrical and we are building heavy water reactors, which can produce 700 megawatt electrical.

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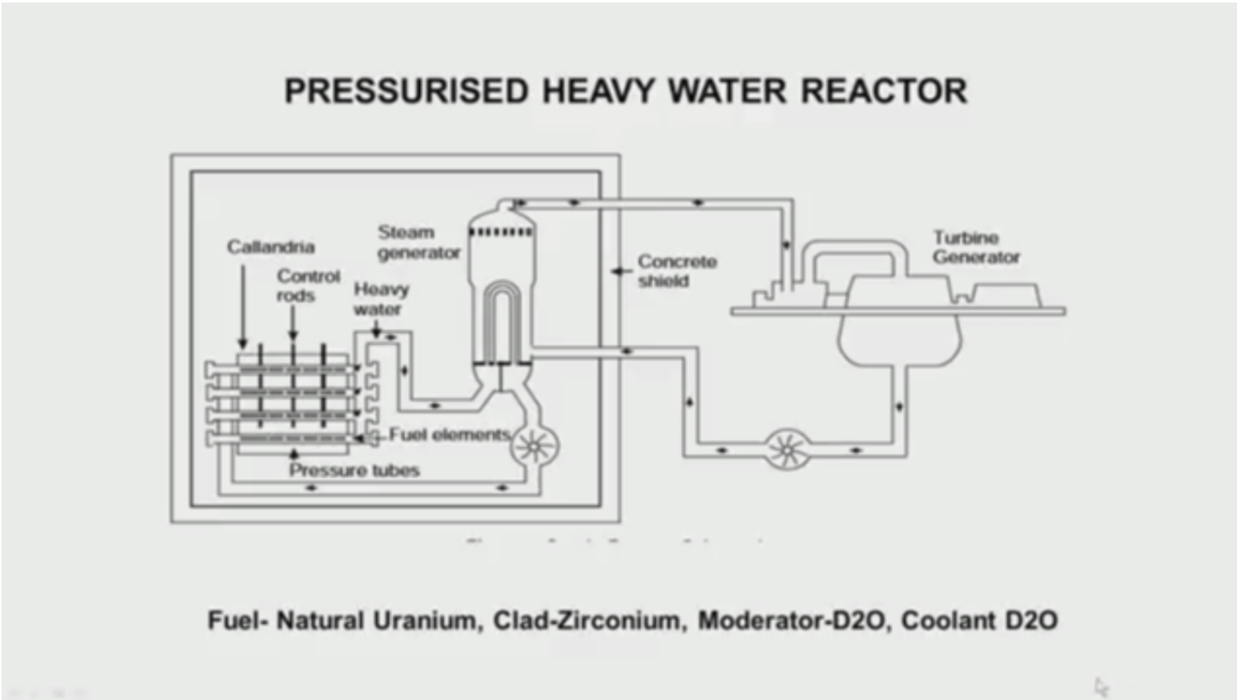

So here you have the reactor core. These pressurized heavy water reactors as is shown here, they have a fuel element, which are put inside horizontal channels. They are called as pressure tubes so the coolant flows from one end to the other. The hot heavy water is the coolant, comes out, goes out, exchanges heat to light water, and then comes back and again, and there are such channels. In 220 megawatt reactor, there are about 306 channels, and the moderator heavy water is put in this big tank called as the Callandria. So it is in a big tank of heavy water in which these pressure tubes are kept in a horizontal position, and then this is how it is done, and the uniqueness of these reactors is they are having on load fueling. Here the fuel is natural Uranium. Clad is Zirconium. Moderator is again heavy water, but these two heavy waters are different. The coolant heavy water flows inside the channels whereas the moderator heavy water is outside.

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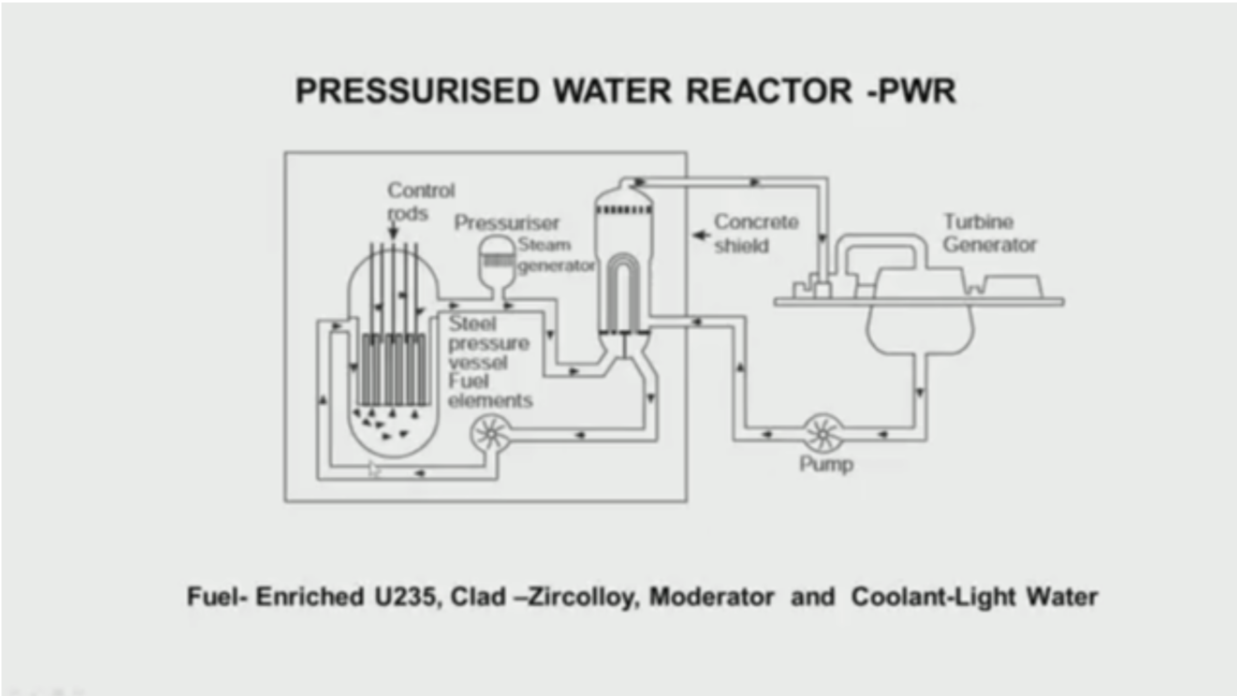

Then the pressurized water reactors. In fact, these pressurized water reactors and the boiling water reactors which comes next, both are called as light water reactors because they use light water. The heavy water reactors initially they were called CANDU because they are based on the CANadian Deuterium Uranium, but in a general way it is called as a pressurized heavy water reactor. Here we use light water and believe it, light water doesn't have that good moderation. It doesn't have that good moderation. The neutrons cannot be slowed down to a good level.

So that means you need to put more fissile atoms to get the same amount of fission reactions. So it requires enriched, so it cannot with 0.7% Uranium 235, light water is not able to make the reactor critical. So you require enrichment.

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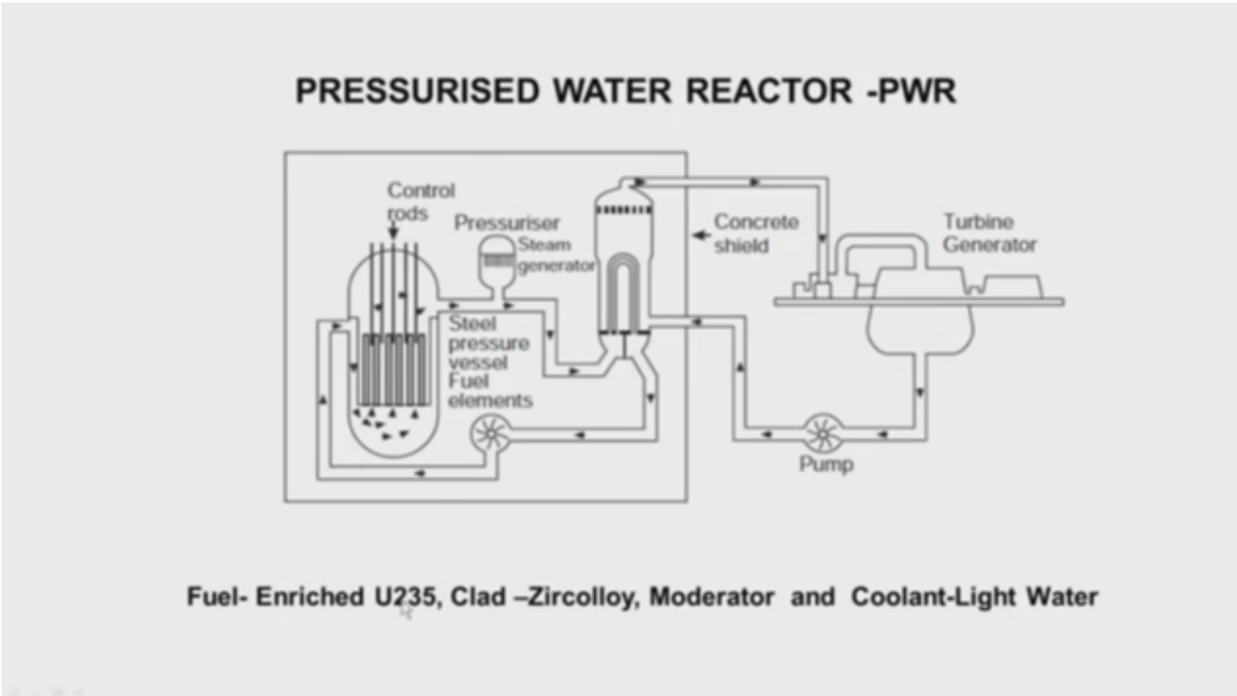

So it used enriched Uranium-235. So here the enrichment is of the order of 3 to 5%, and this enrichment process as I mentioned in my previous lecture is a costly process. Few countries have this enrichment process. So here the clad is Zircaloy, again, moderator and coolant, both are same. They are not separate. The same coolant acts like a moderator and the water which is goes here, it goes into a steam generator, exchanges heat, comes back and they are vertical here, and the feature of this, it doesn't do any onload. You cannot do fuel. You have to shut down the plant and do the refueling, and then you see the steam generator and the -- and the whole reactor is within the concrete building containment as we call and then this is the turbine circuit. As I mentioned, such type of reactors are the maximum number and the reactor at Kudankulam which we are building in India is of this type.

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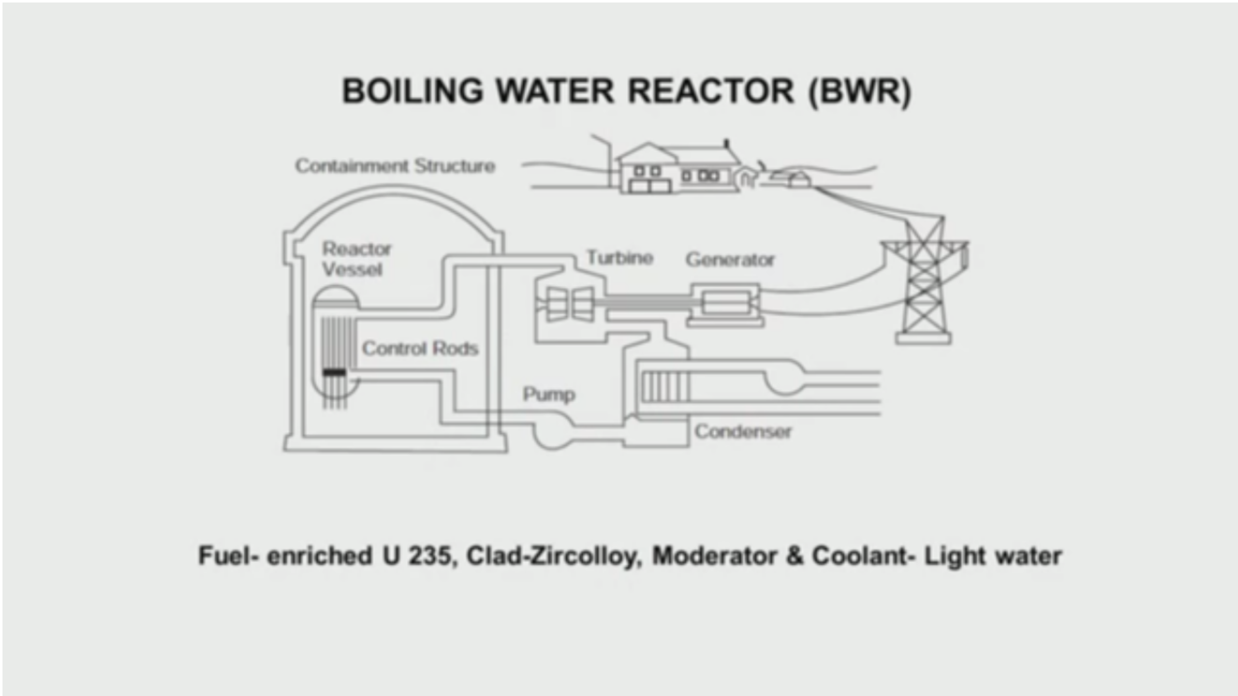

The boiling water reactor. The boiling water reactor, as I mentioned, it has got a single circuit. The reactor coolant enters here, picks up the heat, goes to directly to the turbine. So one way if you see this steam may be active, so the turbine also could be active. So this puts us limit whenever there's a -- a problem on the turbine, you have got to repair it. You have to take some time until the activity dies down and here the -- it is shielded to some extent, the turbine, and this is a generator, and then this is a cooling water, and electricity produced and sent to our house. Here the things are same. Fuel is enriched Uranium-235 up to about 5%. Clad is Zircaloy. Moderator and coolant are light water.

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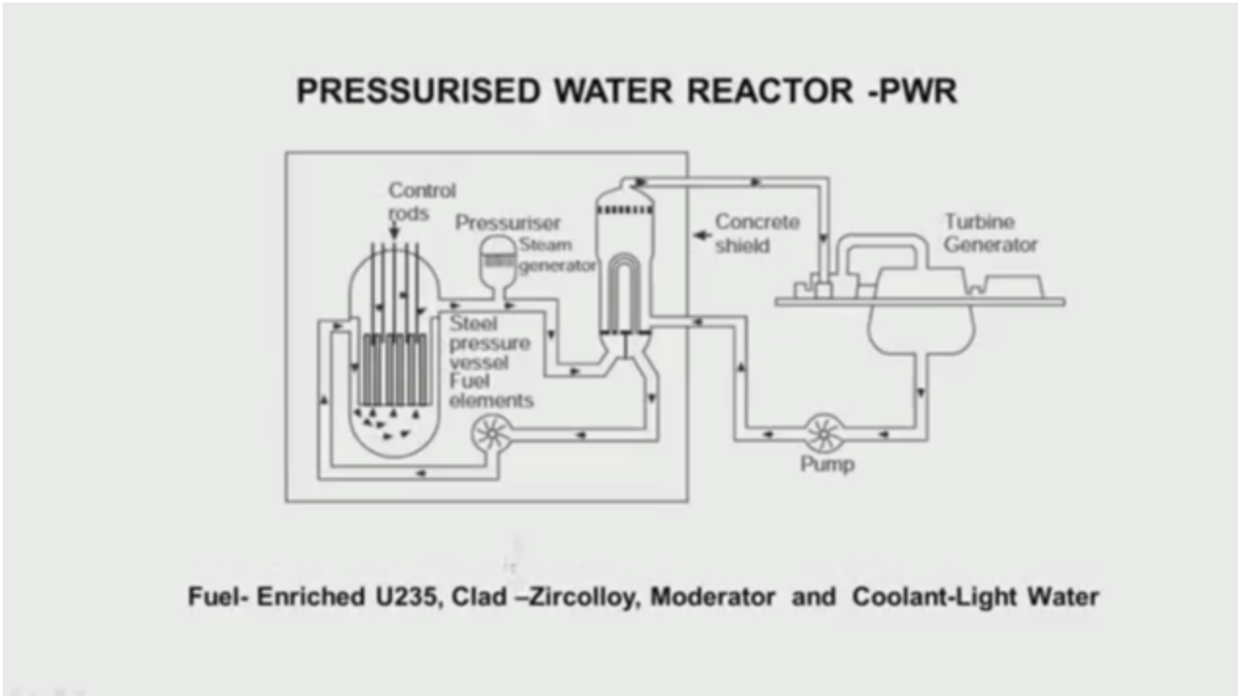

You notice one difference between the pressurized water reactor. Here the control rods are coming from top. The reason is here in this system, everything is water in this. There is no steam at all. It is all water.

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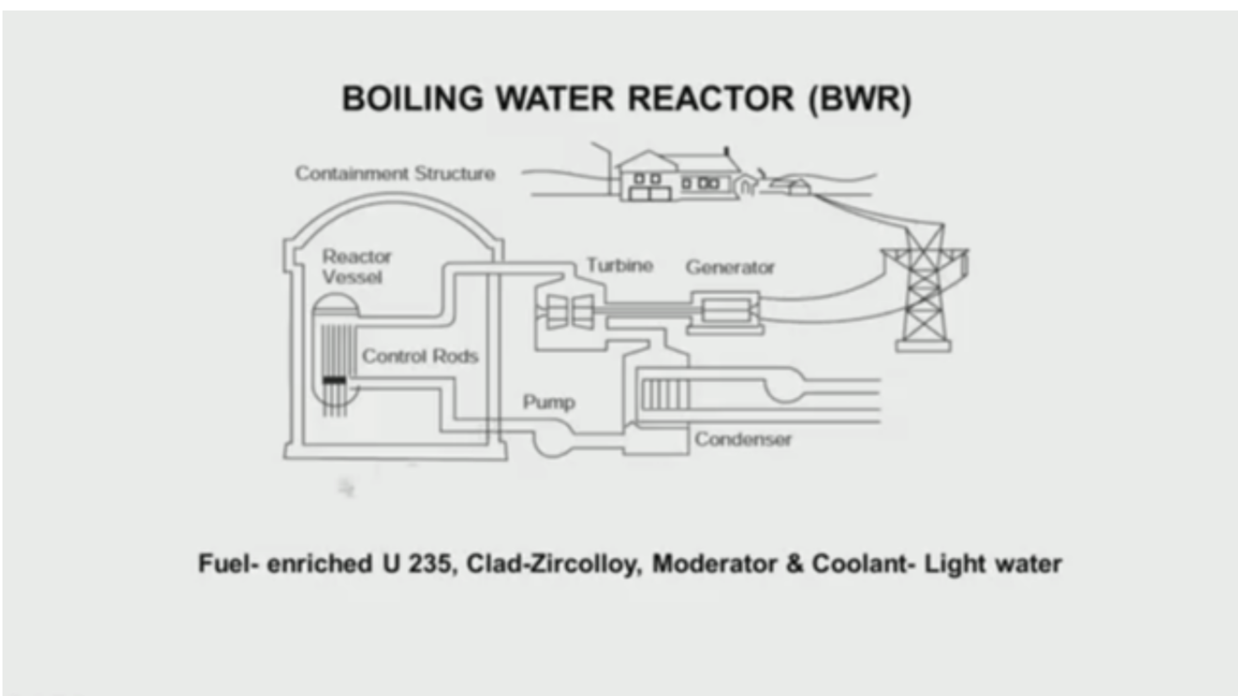

Whereas in a boiling water reactor, steam is produced here and not a full saturated steam. So, and you cannot send the steam mixed with water to the turbine. So you have moisture separators at the top of the reactor, and then only the steam is sent here. Since the moisture separators are here, it puts an obstruction for the control rod. So the control rods are pushed from the bottom. Control rods in a boiling water reactor come from the bottom. This is the difference between the two.

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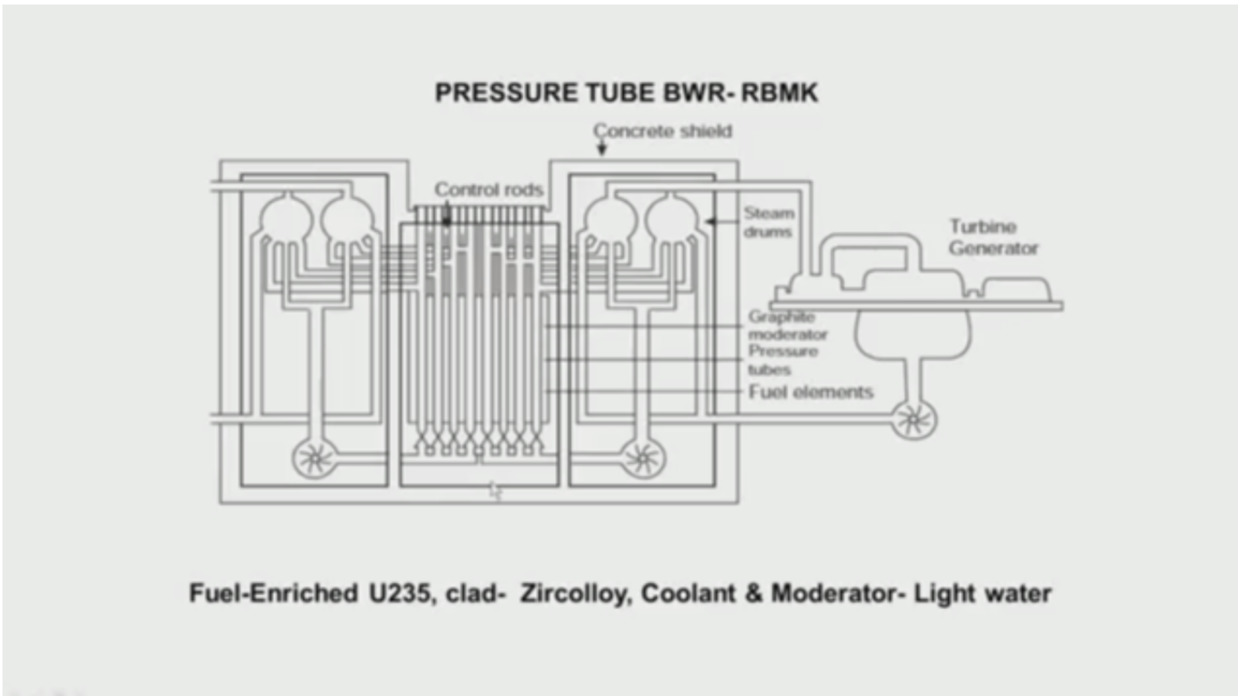

Then this is the RBMK reactor, and the best example of this RBMK reactor I can give you is Chernobyl, and the previous boiling water reactor, we have two such reactors in India. The first two reactors, commercial reactors built at Tarapur were the boiling water reactor. They were given us by the -- given to us in collaboration with USA by the General Electric. We found that it requires enriched Uranium and continued dependence on enriched Uranium is -- on other countries is not good. We found that the heavy water technology requires only natural Uranium and this heavy water technology preparation -- development of technology for heavy water preparation is a chemical process on which we had a good stronghold and we could develop that to a reasonable level. So we went -- we went ahead with heavy water reactors while those developed countries went with enriched Uranium, and boiling water reactors and pressurized water reactors.

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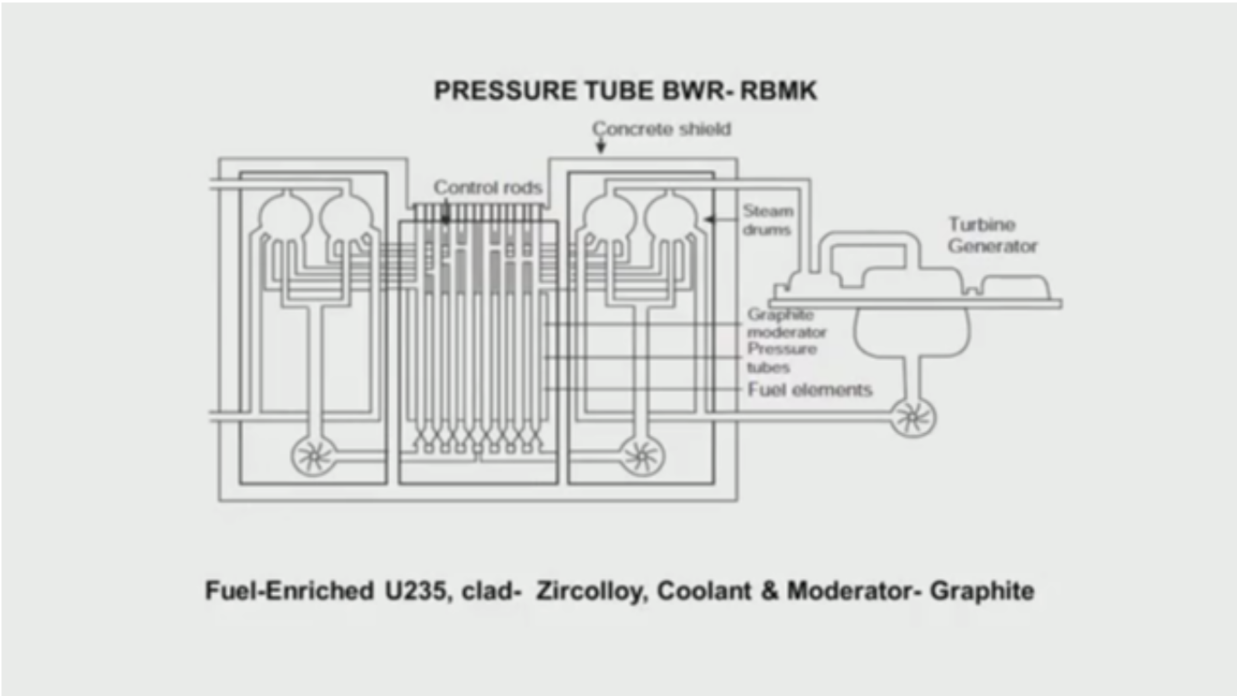

So I will now come to the pressure tube boiling water reactor called as the RBMK. Here the channels are vertical channels. They are all pressure tubes. Just as a pressure tube in a heavy water reactor in horizontal, they are vertical. They use this concept because they found that making a pressure tube is easier because it is a small diameter whereas instead of making a large pressure vessel of a bigger diameter in those days. So they put up on this sort of a design and it is just similar to a light water reactor, but the difference is the moderator is graphite. So lot of graphite moderator is put, and the steam comes out, and these are drum where the steam is separated. It is sent to a turbine and runs the generator. This was used in the Chernobyl reactor.

One difference is this particular reactor type didn't have the containment. That is a very important aspect and compared to the boiling water reactor, this used graphite as a moderator, and as we know in the Chernobyl reactor because of the overpower, the graphite got heated up and caught fire that they actually added fuel to the fire.

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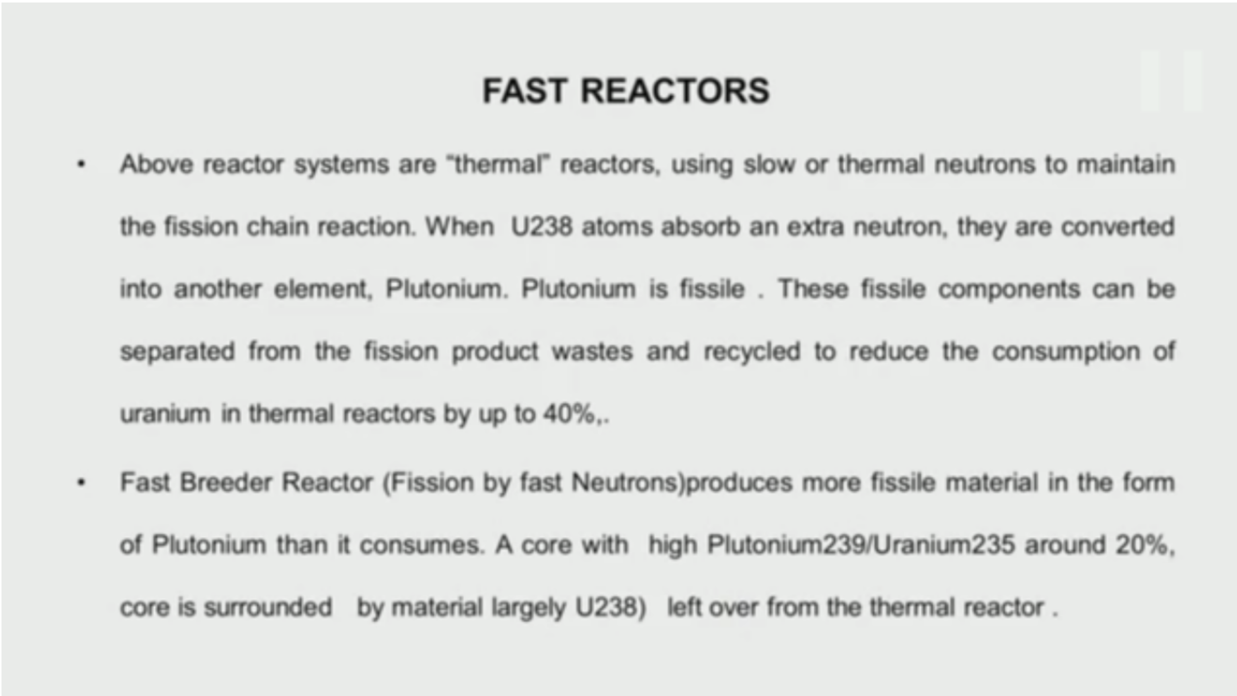

Now we move on to the fast reactors. As I mentioned in the case of light water reactors, the pressurized water, the boiling water reactor or the RBMK, the fission is by slow or thermal neutrons whereas in a fast reactor, it is by fast neutrons and why fast neutrons? Uranium 238 absorbs a neutron and gets converted to Plutonium, which is a fissile element. Now a core for a fast reactor most essentially consists of higher amount of fissionable material because the cross sections or the probability of a fission reaction is low at high energies. So it consists of a mixture of Plutonium 239 and Uranium 235 of the order of about 20%, but some of the research reactors wherein you want to simulate the neutron flux of larger reactors, you have something like 70 to 80%, and now this Uranium 238 we just don't go and get again. We -- it remains from the used fuel of the fast thermal reactors, which we put in the fast reactors. So we are basically utilizing the waste of the thermal reactor in a fast reactor and getting it converted.

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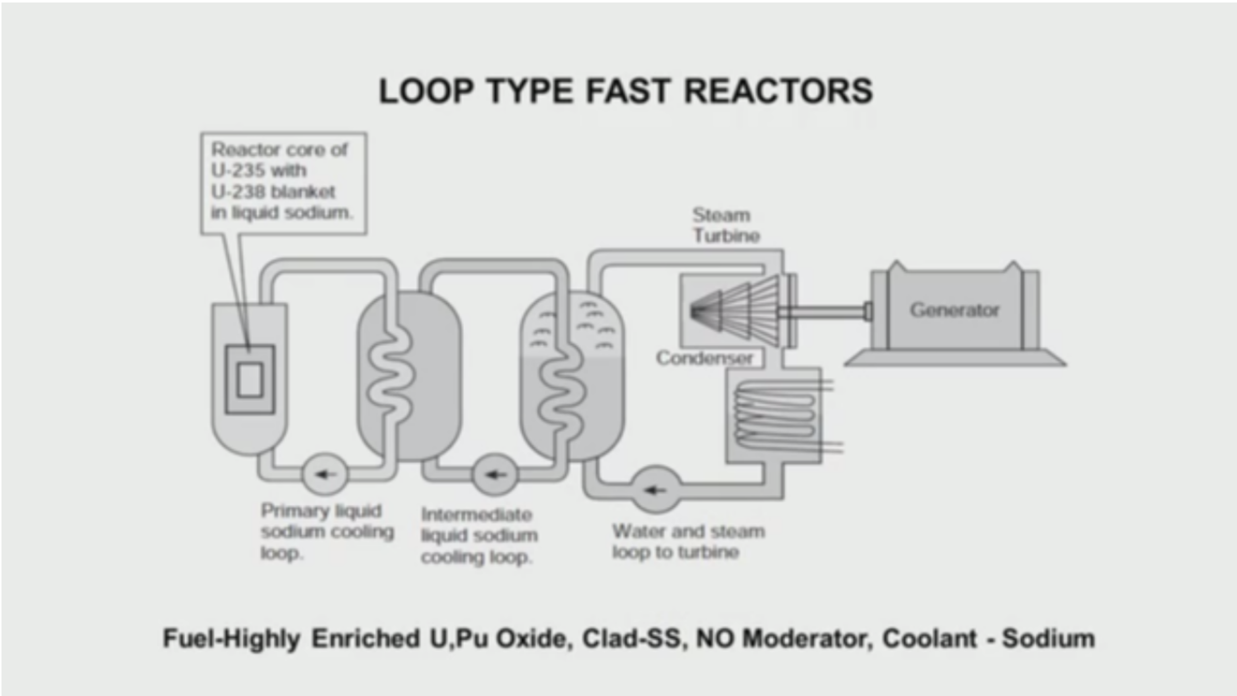

There have been two concepts of the fast reactors. One is called as a loop type. Other is called as a pool type. In the loop type, all components are kept separately and connected by pipes. You have the reactor core and sodium is the coolant, which removes heat from the core and exchanges heat to another sodium in another -- in a heat exchanger. This is called as intermediate heat exchanger and this sodium in turn gives heat to water which produces steam to run a turbine. Rest of the things remain same.

You might wonder in a boiling water reactor we had just one loop. In a pressurized water we had three -- we had two loops. Here we have three loops. It's a major reason. Sodium is used as a coolant in fast reactors because we are able to reach high temperatures. Sodium has got a boiling point of 930 degree centigrade and because of that without pressurizing the system, we can go to a high temperature in Sodium unlike water. We reach something like 500 to 525 degree centigrade temperature, and we are able to produce steam around 500 degree centigrade, which is very close to the fossil fuel condition. So the efficiencies of steam cycle here is of the order of 38 to 40% whereas in a light water reactor like a boiling water reactor or a pressurized water reactor, the efficiencies are around 30 to 32% only, and this does make a difference. More the efficiency, less the amount of fuel and less the waste. But why these three circuits? Why not get rid of the second Sodium circuit?

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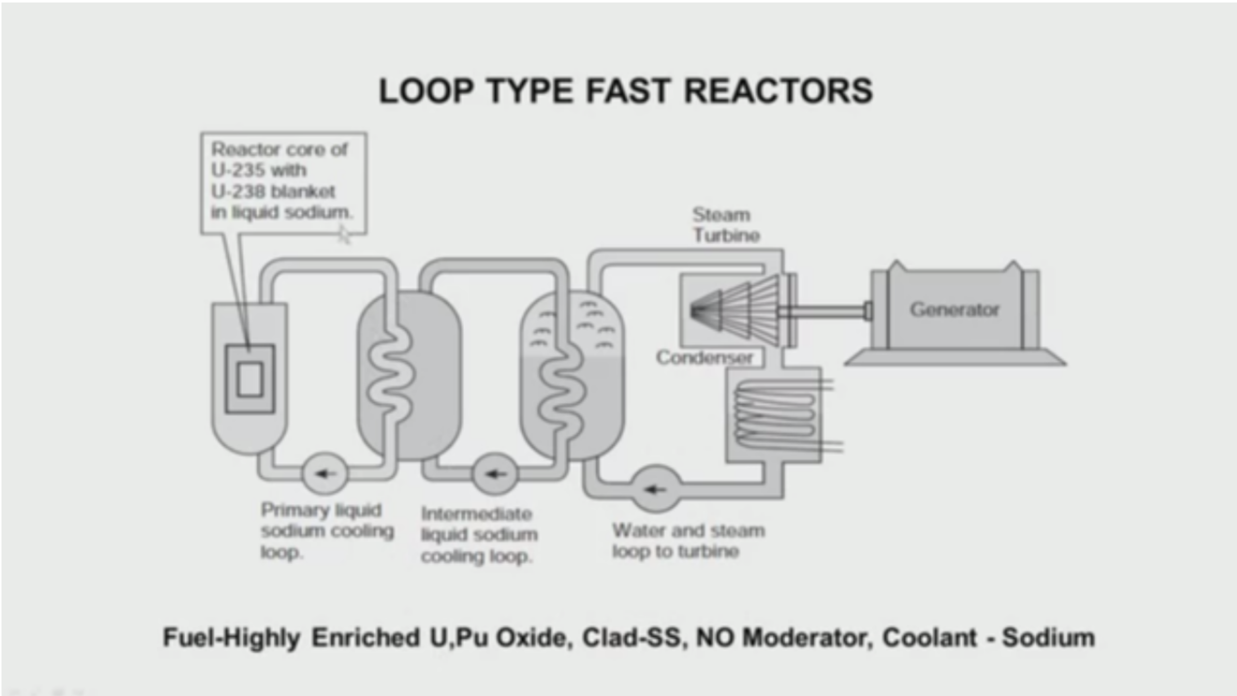

Unfortunately, you see in life everywhere you have to get an advantage, you have to pay a price. This Sodium has got a good affinity for water and air. Sodium if you put outside, it burns. Sodium if it comes in contact with water, it forms exothermic reaction, producing sodium hydroxide and hydrogen, and hydrogen is a moderating material. We have now designed a fast reactor without a moderating material. What will happen if a moderating material gets into the reactor? Think about it. We have said no moderation, so all fast neutrons we have provided lot of fissile material. Now this moderating materials get inside the reactor. If they will become thermalize, slow neutrons, the fission reaction probability will increase and the whole thing may become supercritical. So from a safety angle, we don't want any leakage in the steam generator which results in a Sodium water reaction to affect the core.

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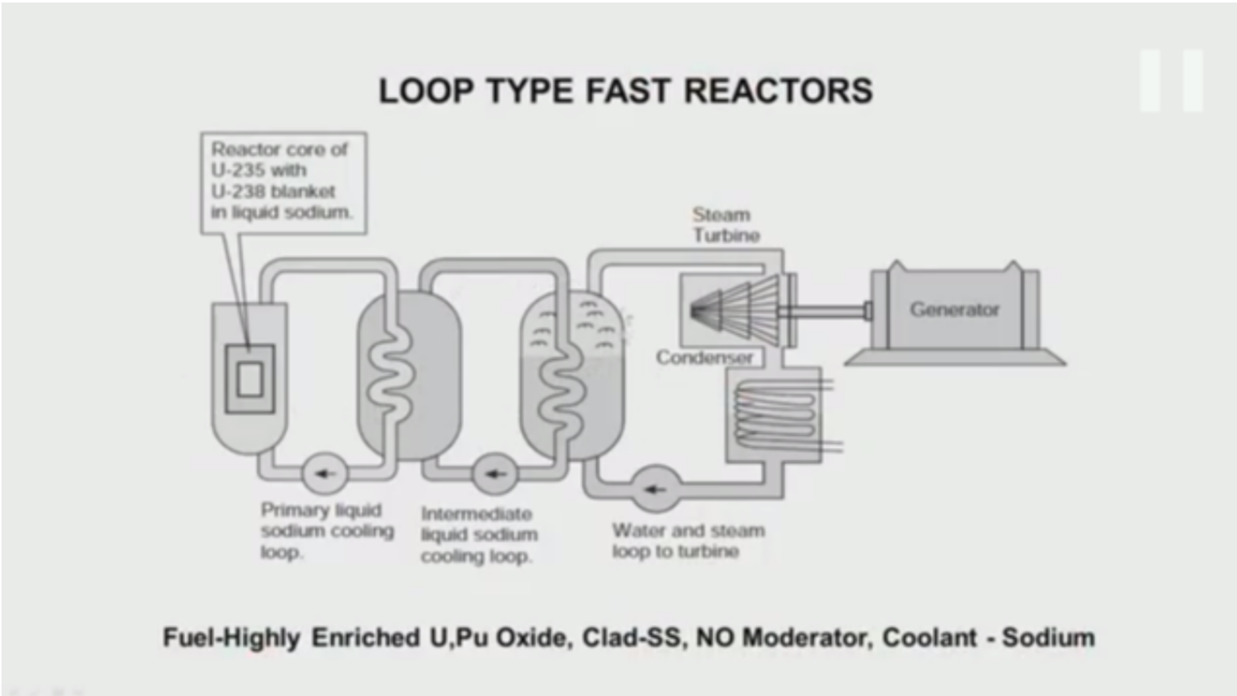

So we have an intermediate circuit. This is designed to withstand the pressures of a sodium water reaction. So that is a reason why we have two such circuits. They as I mentioned enriched Plutonium, Plutonium oxide is a fuel. Clad is stainless steel. No moderator and coolant is Sodium.

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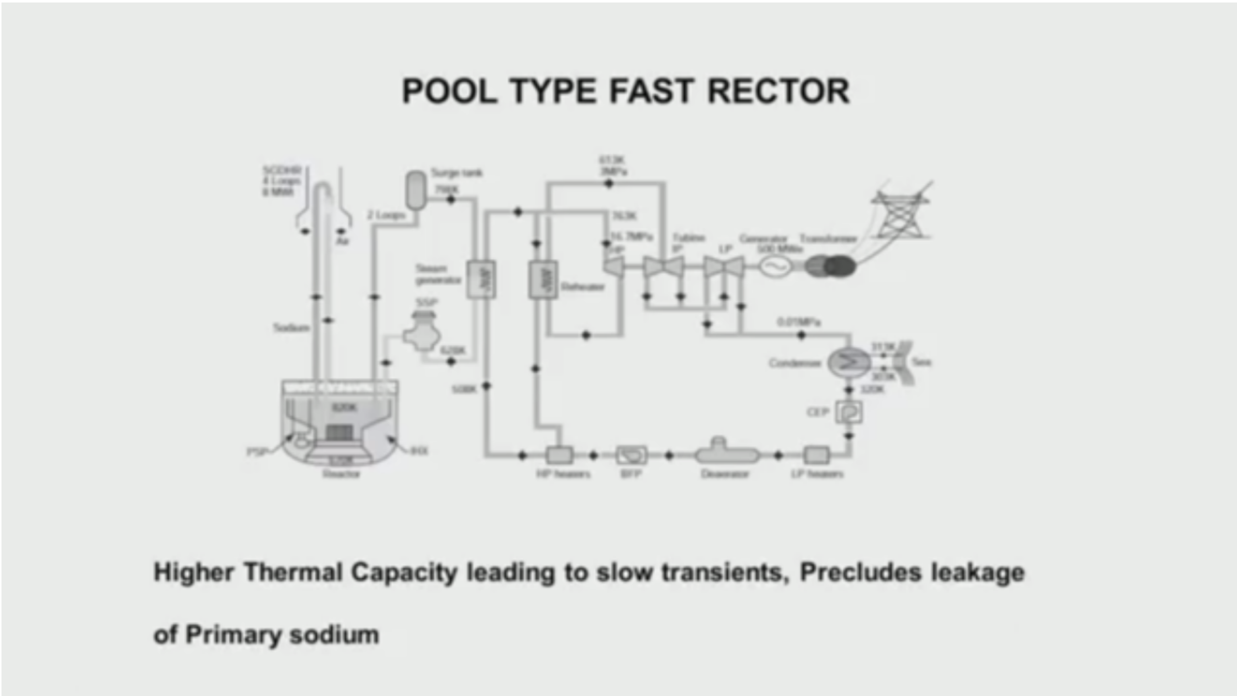

In the pool type reactor, the difference is very simple. We have put all the primary components in a big pool. This is the core. We have the intermediate heat exchanger. We have the pump here which pumps into the core that goes to the HX and comes out to the cold pool. The whole thing is in a single vessel and rest of the circuits are same.

What is the advantage of this sort of a concept? You see here the size is big. Cold sodium, hot sodium, what happens in case of an event let us say there is a power failure and the reactor is shut down? The coolant flow will come down. Temperatures surely will come down initially because of shutdown. Then the temperature is raised in case the cooling is not. The rate of temperature rise should be low. Then it gives you operator enough time to handle the situation, and that is the main advantage of a pool-type reactor. The thermal capacity, large amount of Sodium is there. So it will take less, you know, more time to raise by the same amount. So the transients introduced thermal transients are less. That is one big advantage and the second advantage, we saw pipes in the loop type reactor.

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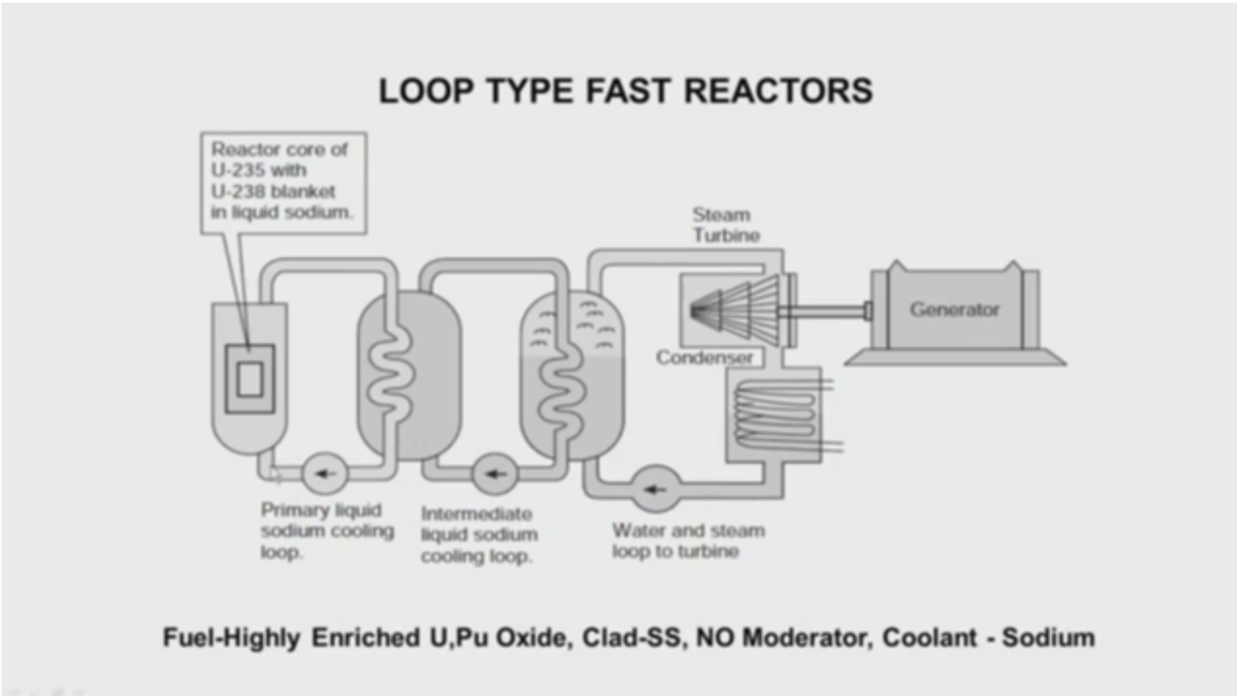

So in case there's a leak here, radioactive Sodium will leak out, but here in the pool type, we don't have that. Any leakage is there, it will be contained within this large vessel and this is a big advantage of a pool type reactor. Earlier reactors, small reactors are generally of the loop type have been built. Now the bigger reactors are pool type. In India our fast breeder test reactor, which is already operating at Kalpakkam since 1985 is a loop type reactor while PFBR which is likely to go critically in the next one or two years is going to be a pool type reactor.

Now we have had a look at the different types of reactors. You might see so many designs have been there, but slowly people are getting a consensus to consolidate the efforts of research and try to corner or converge on few reactor types on which we do more work to have more and more safer reactors. They are called as the generation 4 reactors about which we will see in the next lecture. Thank you.

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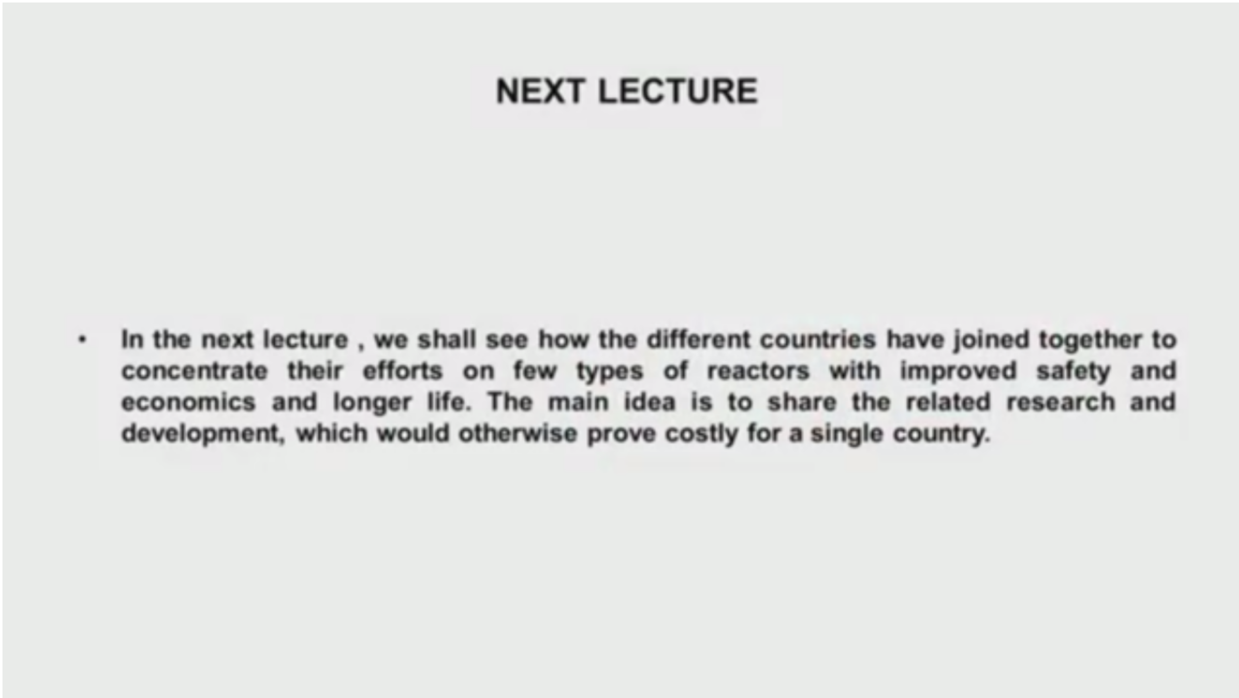

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